Saturday Morning Physics

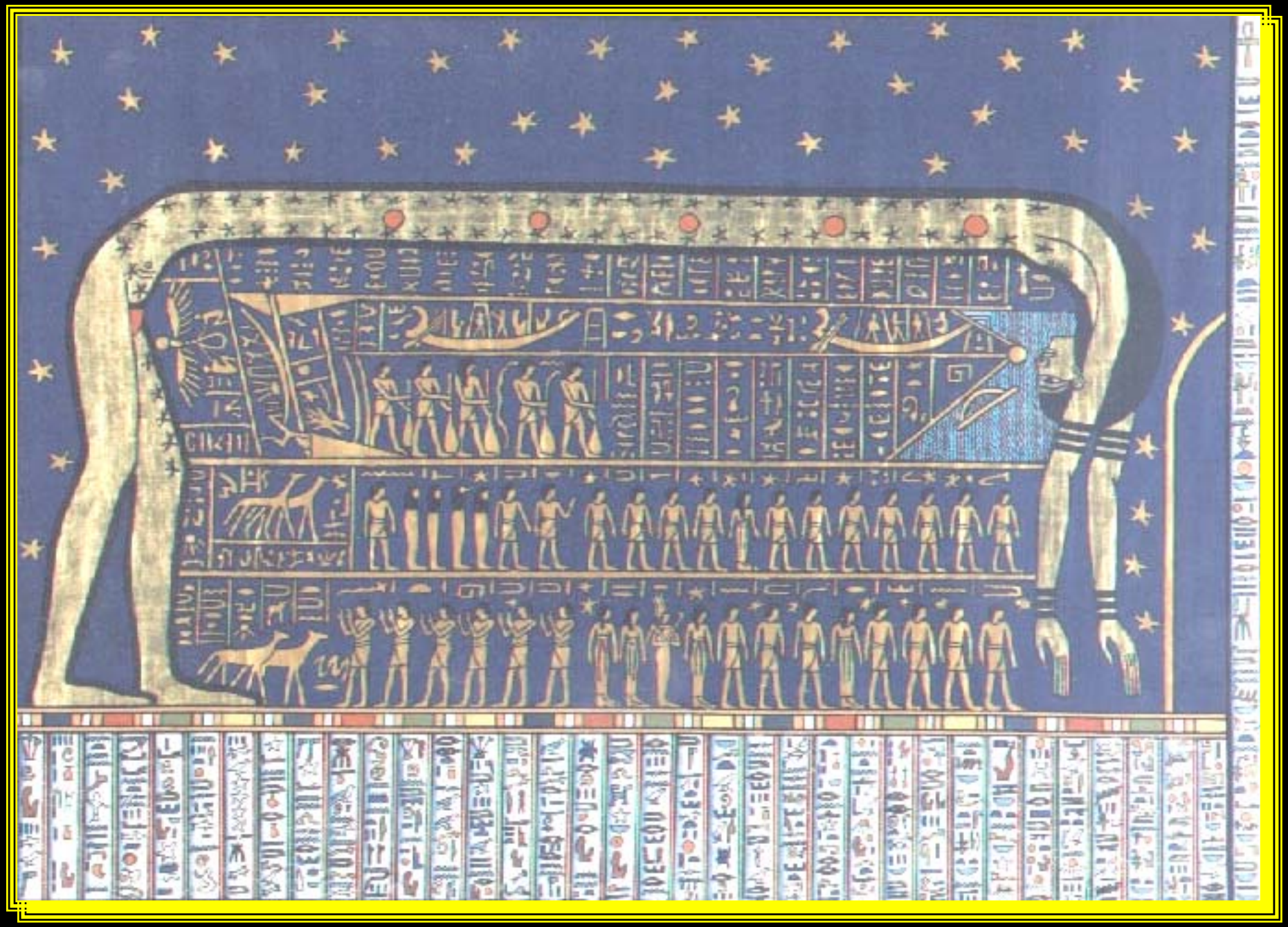
THE BIG BANG

Rocky Kolb
Fermilab and the
University of Chicago

Fermilab

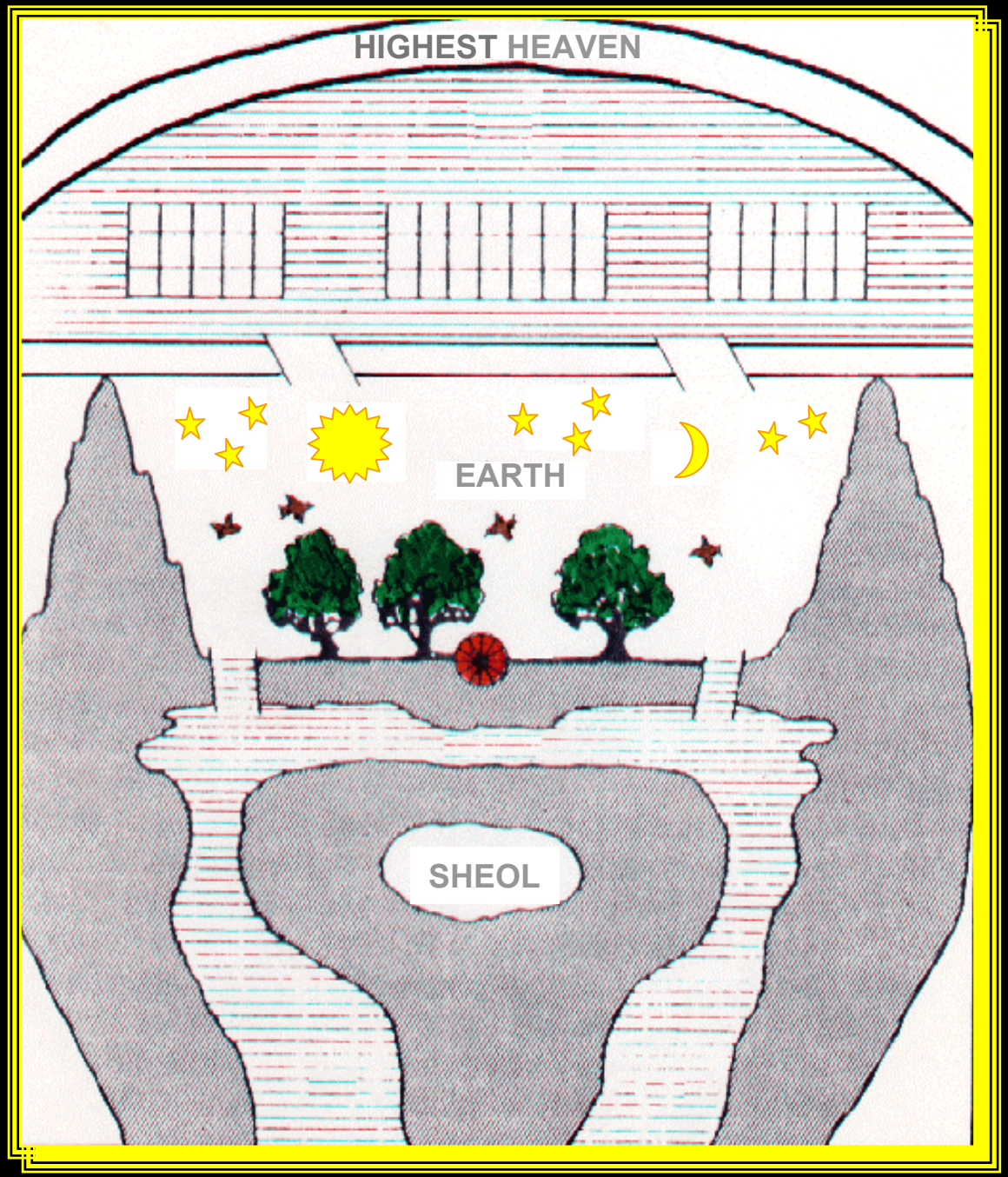
January 13, 2001

A view of the universe, circa 2001 B.C.



Some of the 597 experimentalists on CDF

A view of the universe, circa 1001 A.D.*



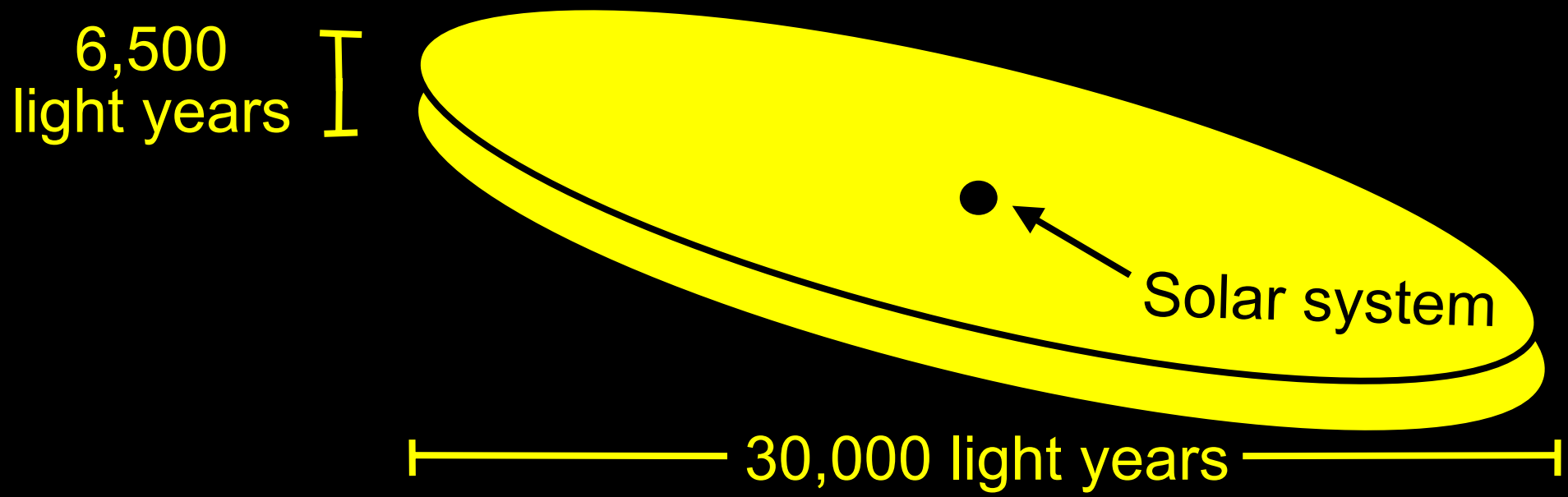
*and circa 2001 A.D. in parts of Kansas

A view of the universe, circa 1901 A.D.

Kapteyn Universe

1) Composition: Starz' in the 'hood

2) Arrangement:

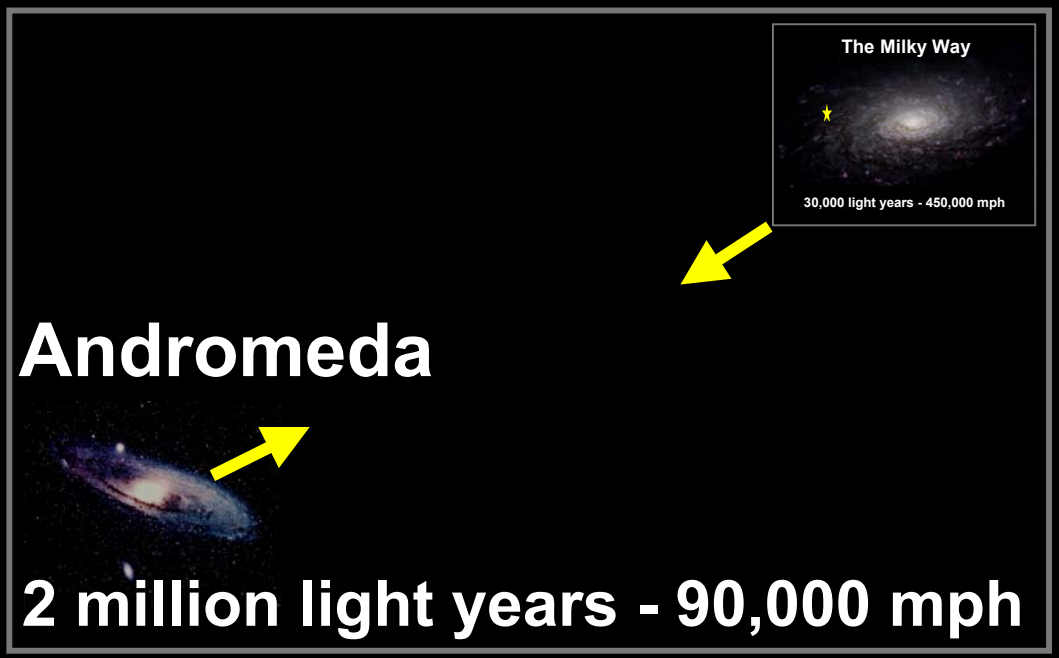


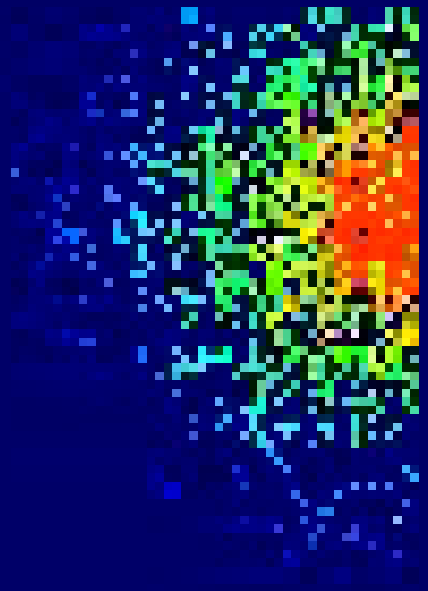
3) Origin: ?

Space, time, and motion in the universe

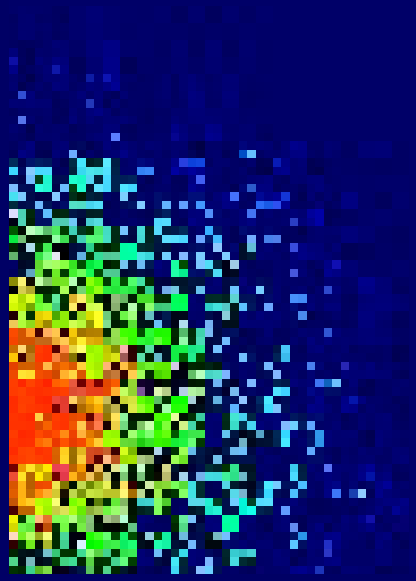

ANDROMEDA
GALAXY

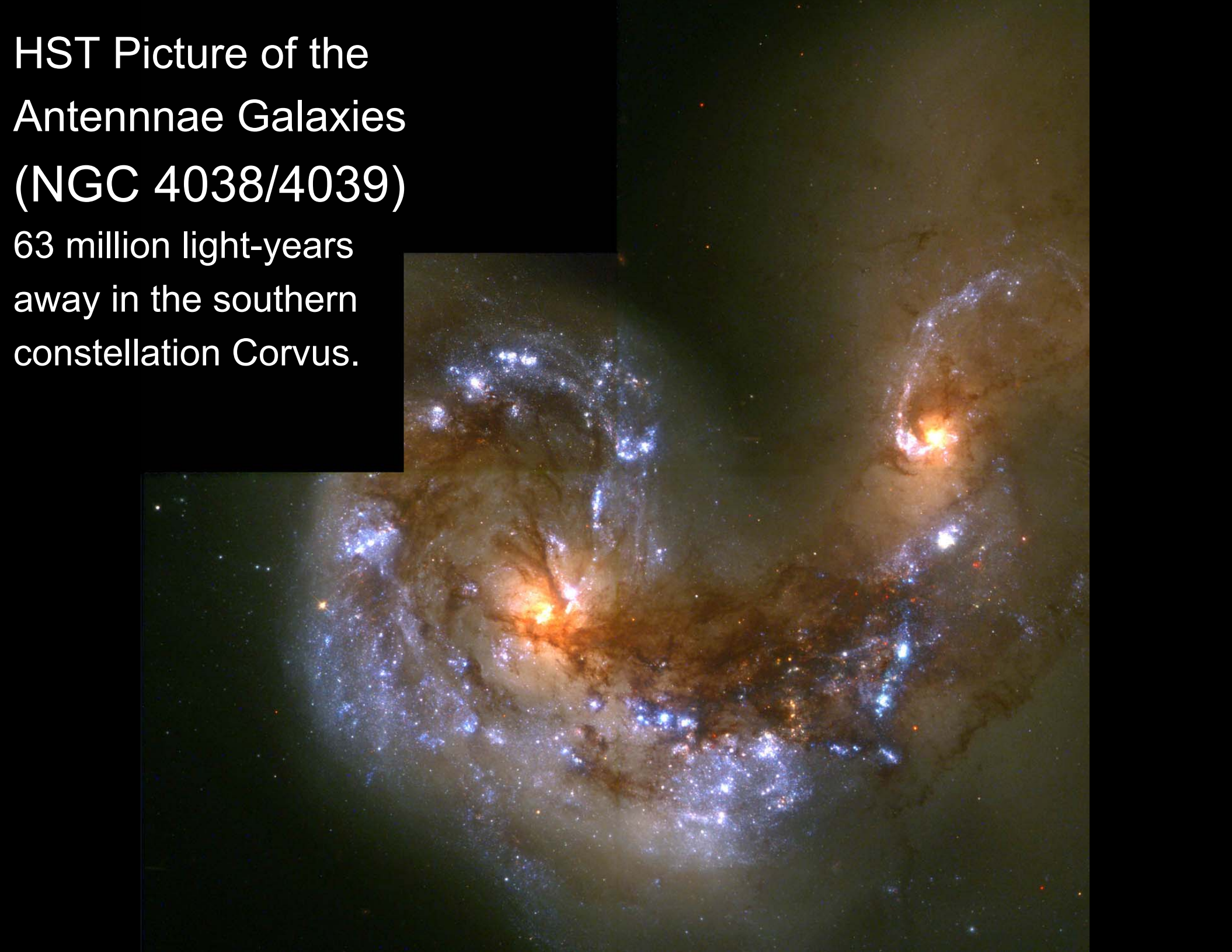
Space, time, and motion in the universe





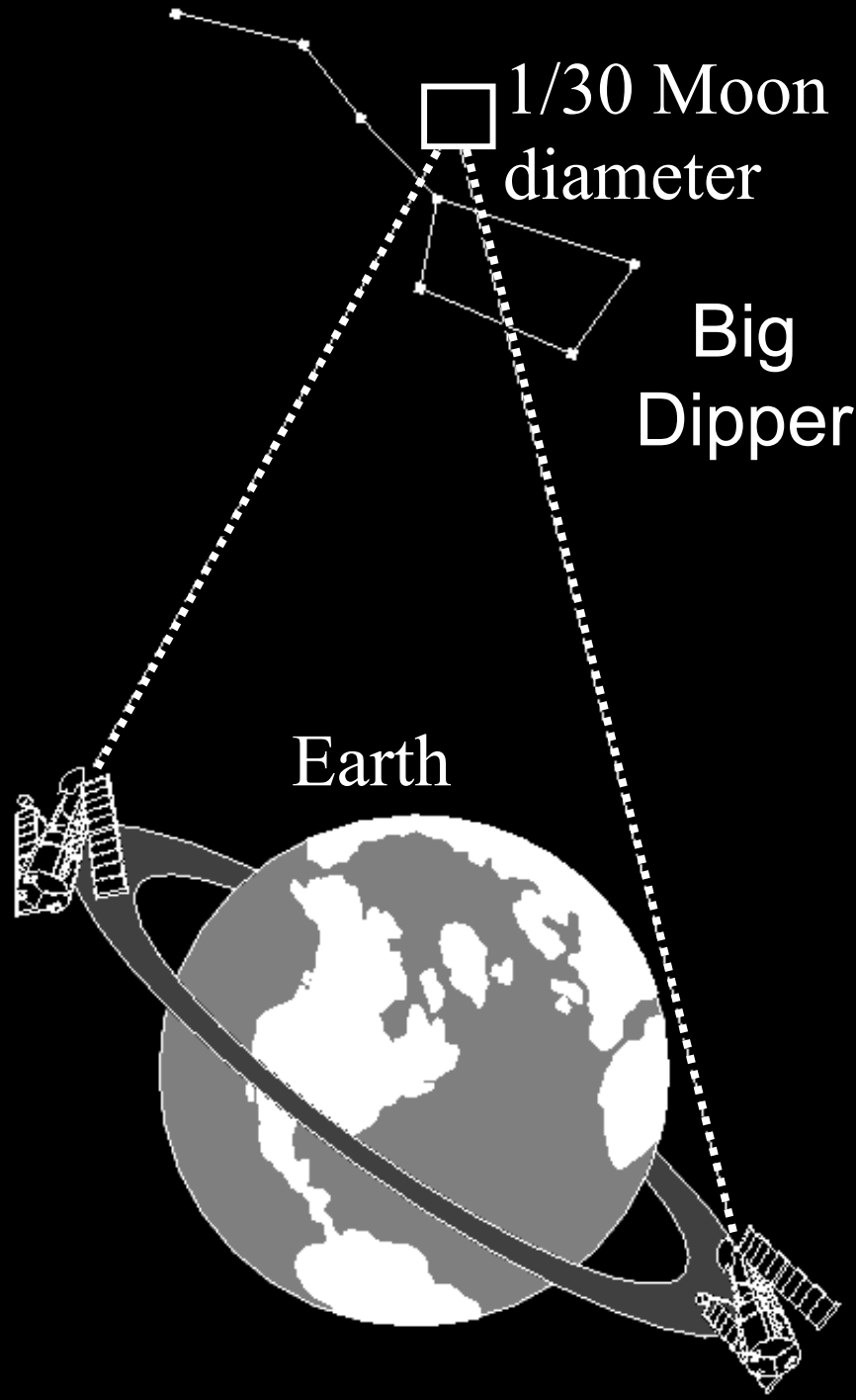
Simulation from Greg Bothun
University of Oregon




HST Picture of the
Antennnae Galaxies
(NGC 4038/4039)
63 million light-years
away in the southern
constellation Corvus.

A view of the universe, circa 2001 A.D.

Hubble Deep Field



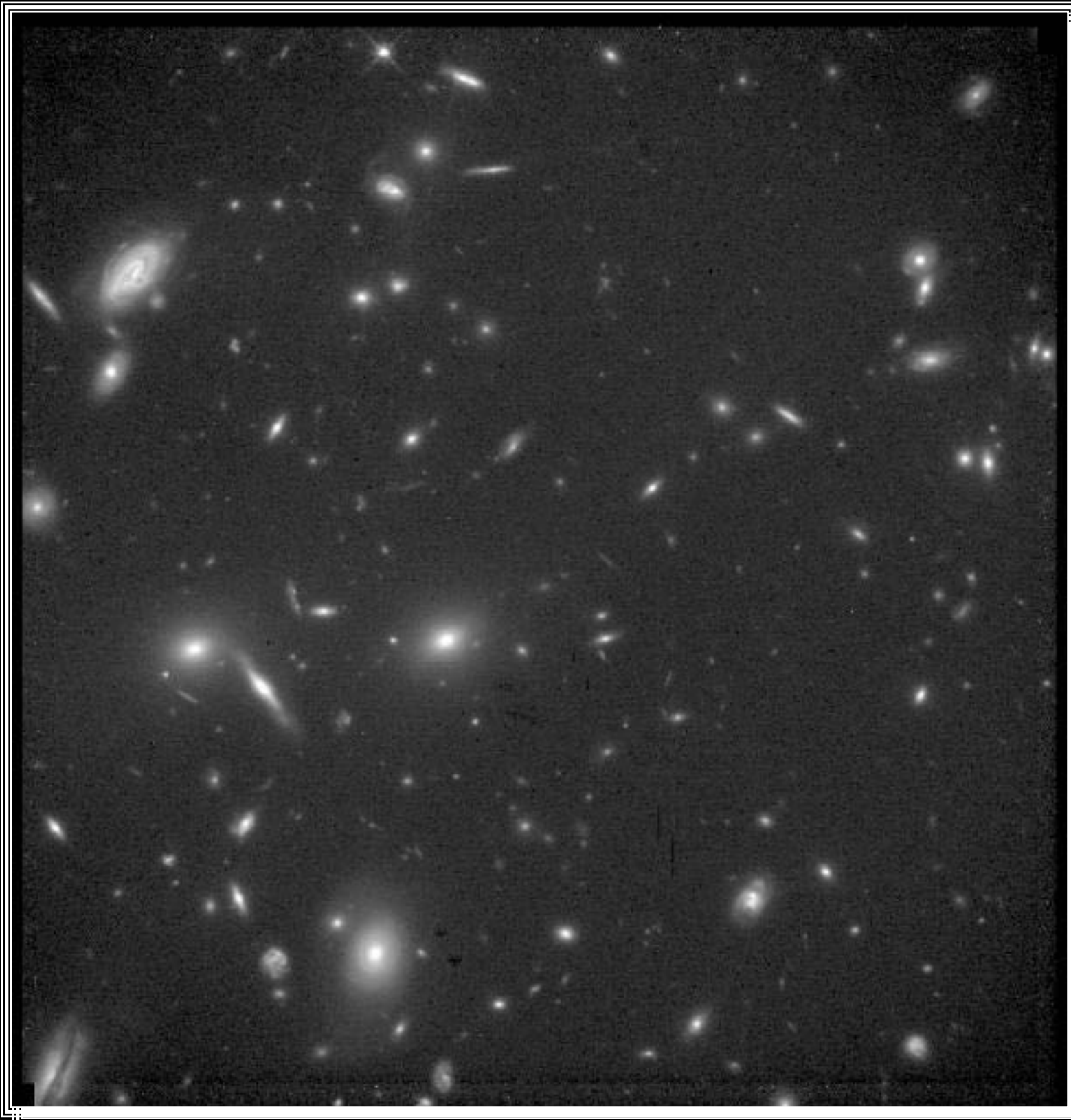
Hubble Deep Field

UNIVERSE OF GALAXIES

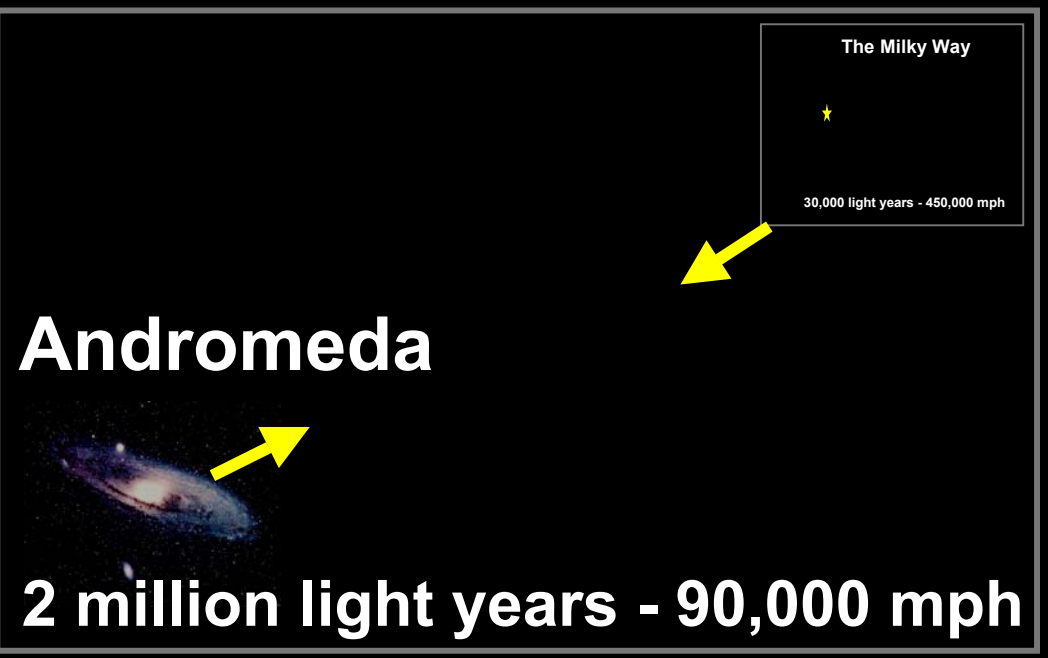
3000 here →

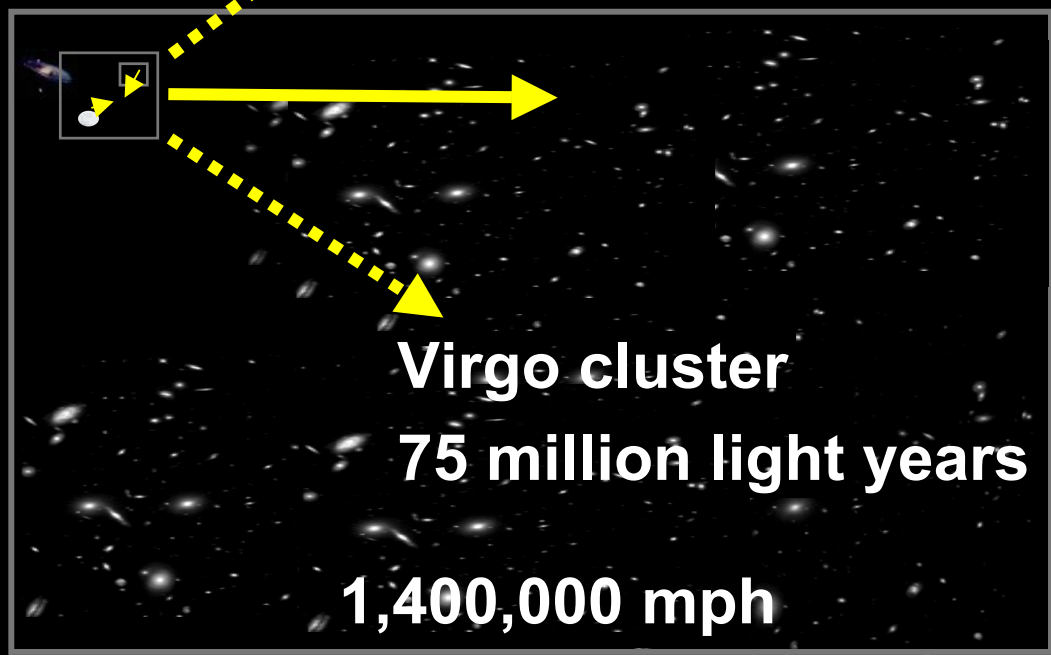
50 billion over entire sky

Cluster of Galaxies

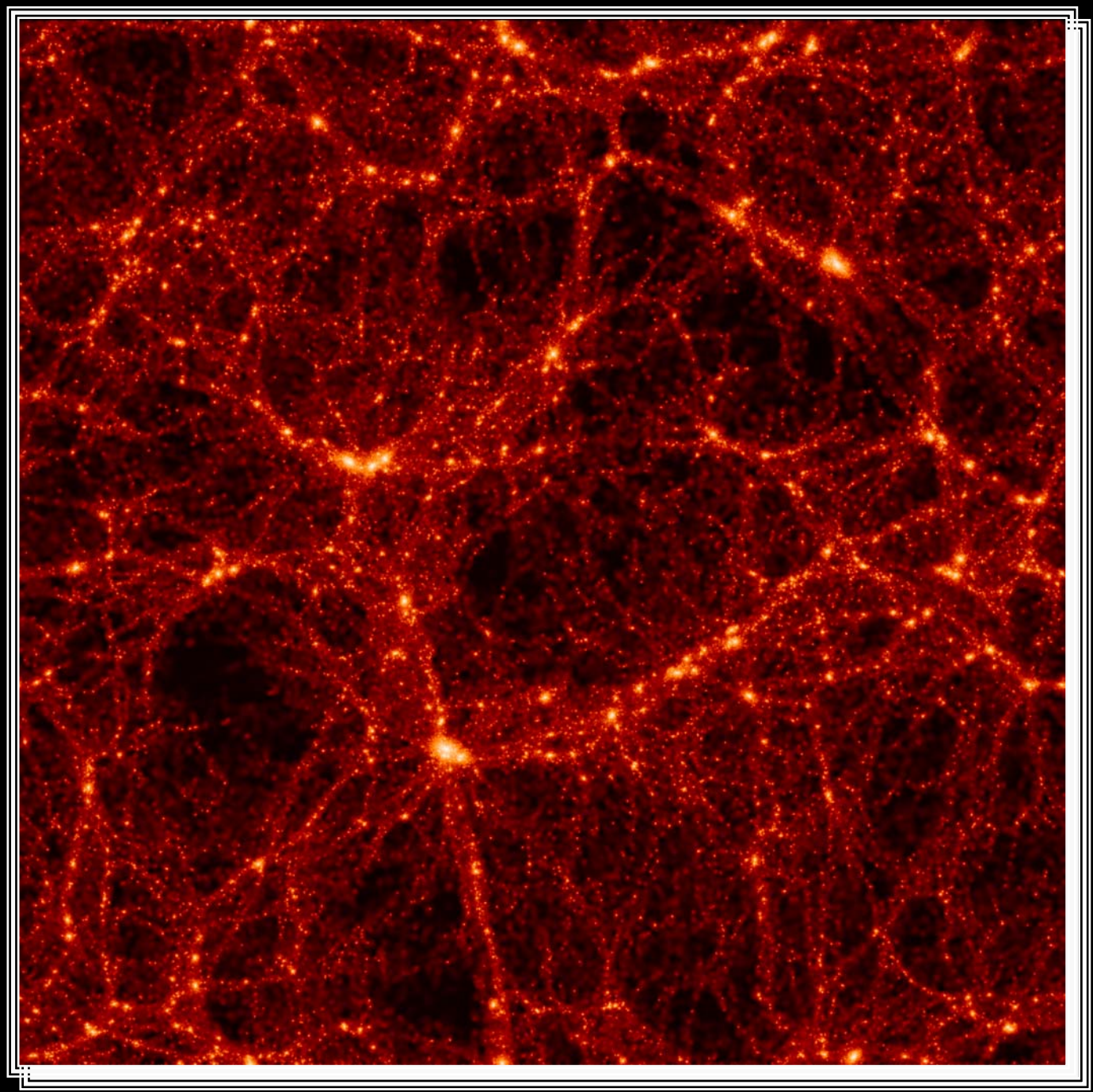


Space, time, and motion in the universe





The Cosmic Web



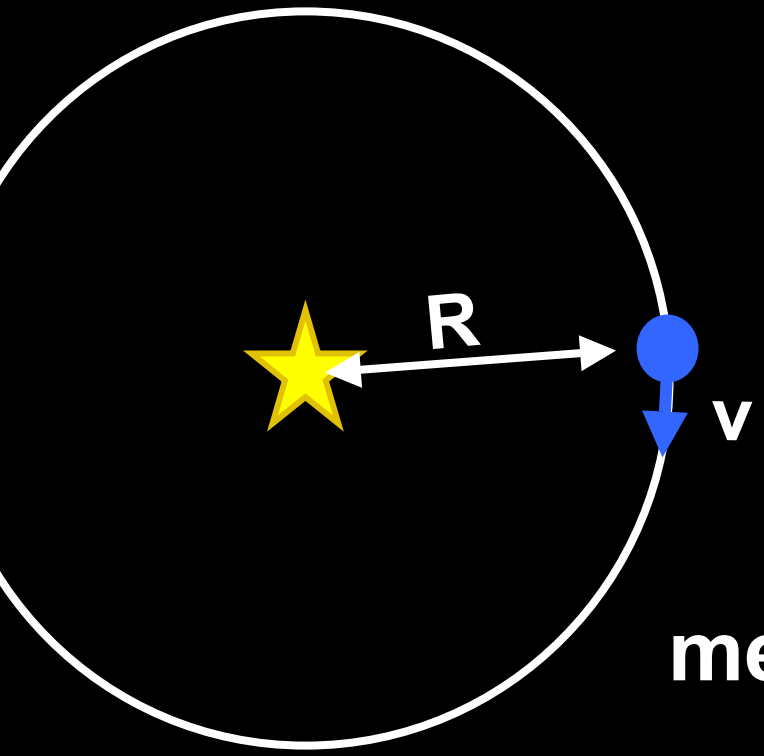
The VIRGO Project

Galaxies: Building blocks of the (visible) universe

Missing Pieces

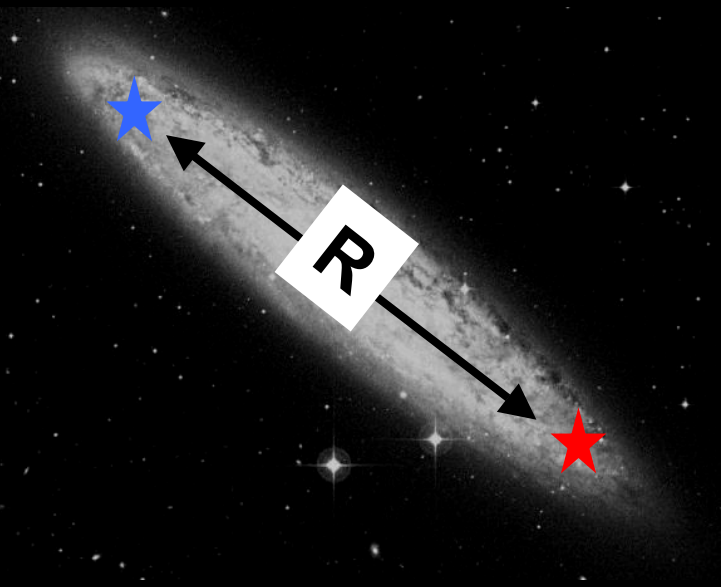
Dark Matter


NGC253 in Sculptor



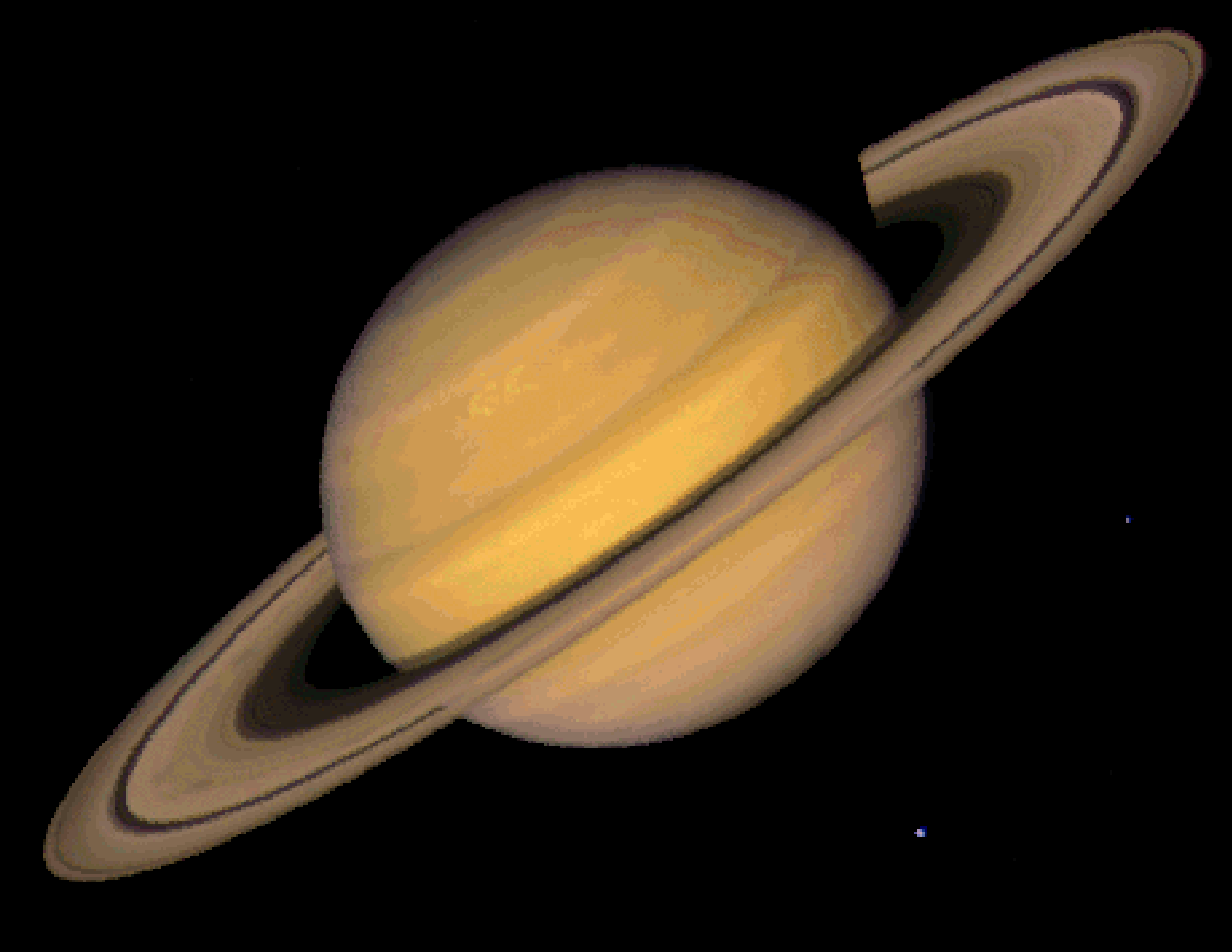
$$\frac{v^2}{R} = \frac{G\,M_{SUN}}{R^2}$$

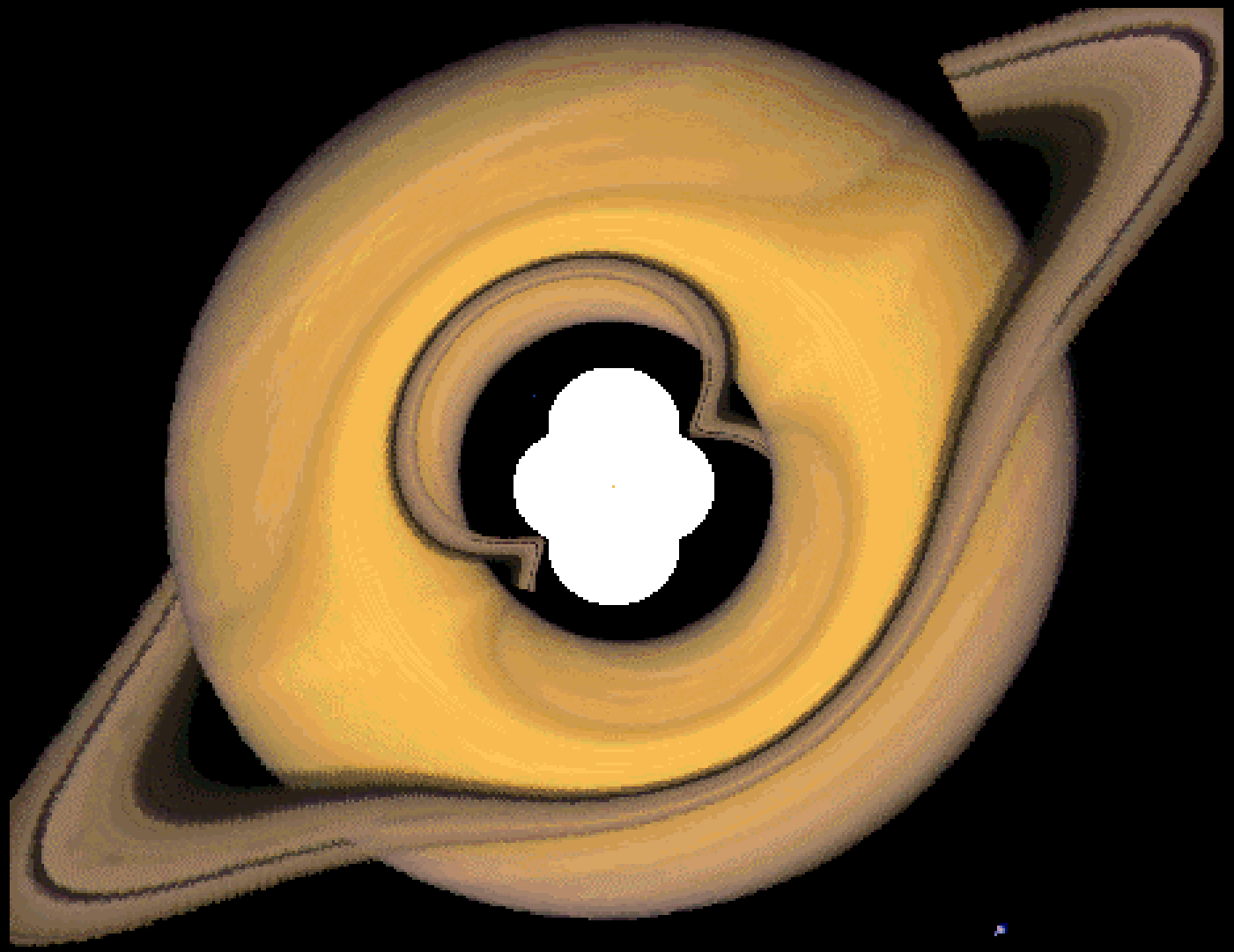
measure v & R ⇒ M_{SUN}

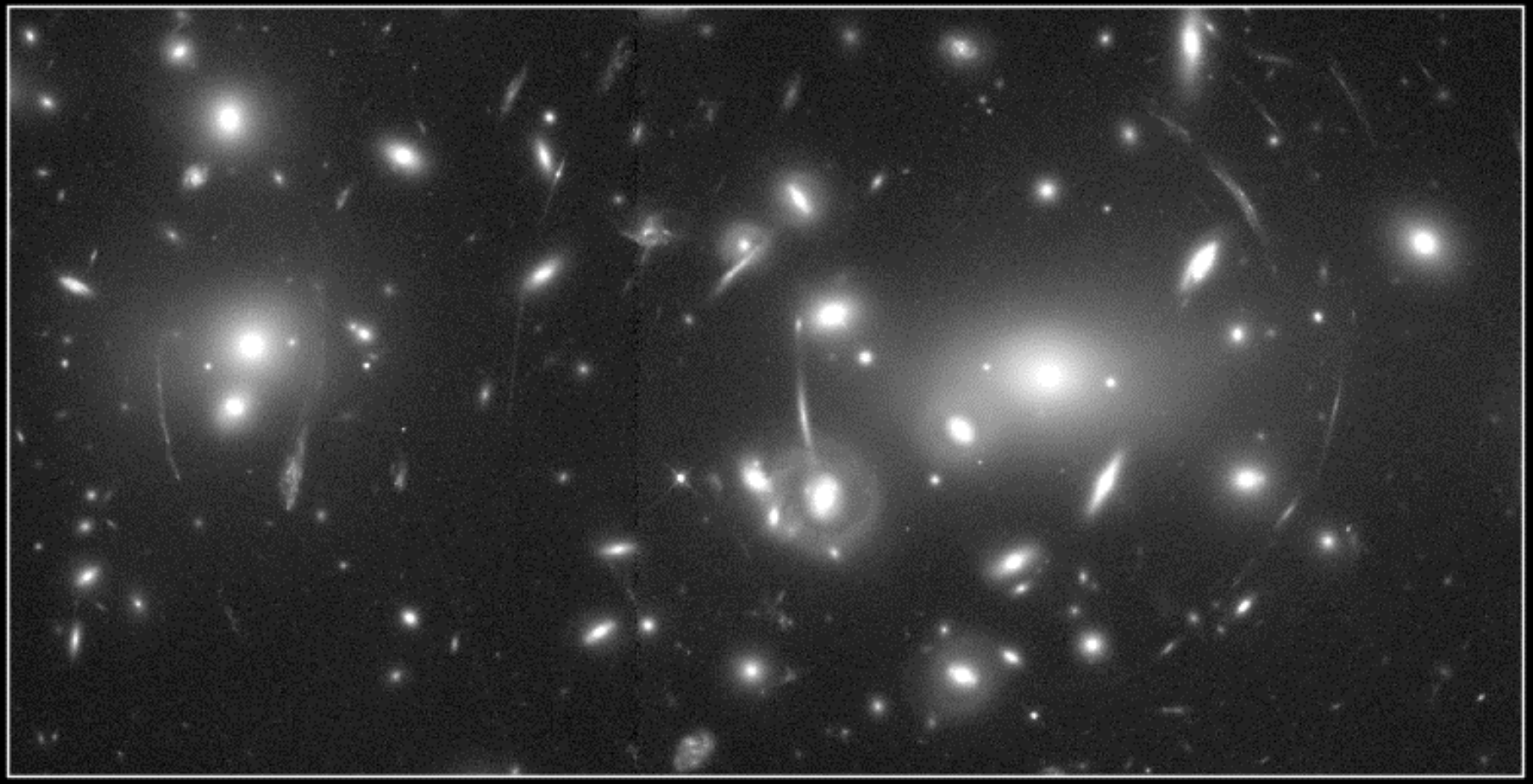


$$\frac{v^2}{R} = \frac{G\,M_{GALAXY}}{R^2}$$

measure v & R ⇒ M_{GALAXY}







Gravitational Lens in Abell 2218

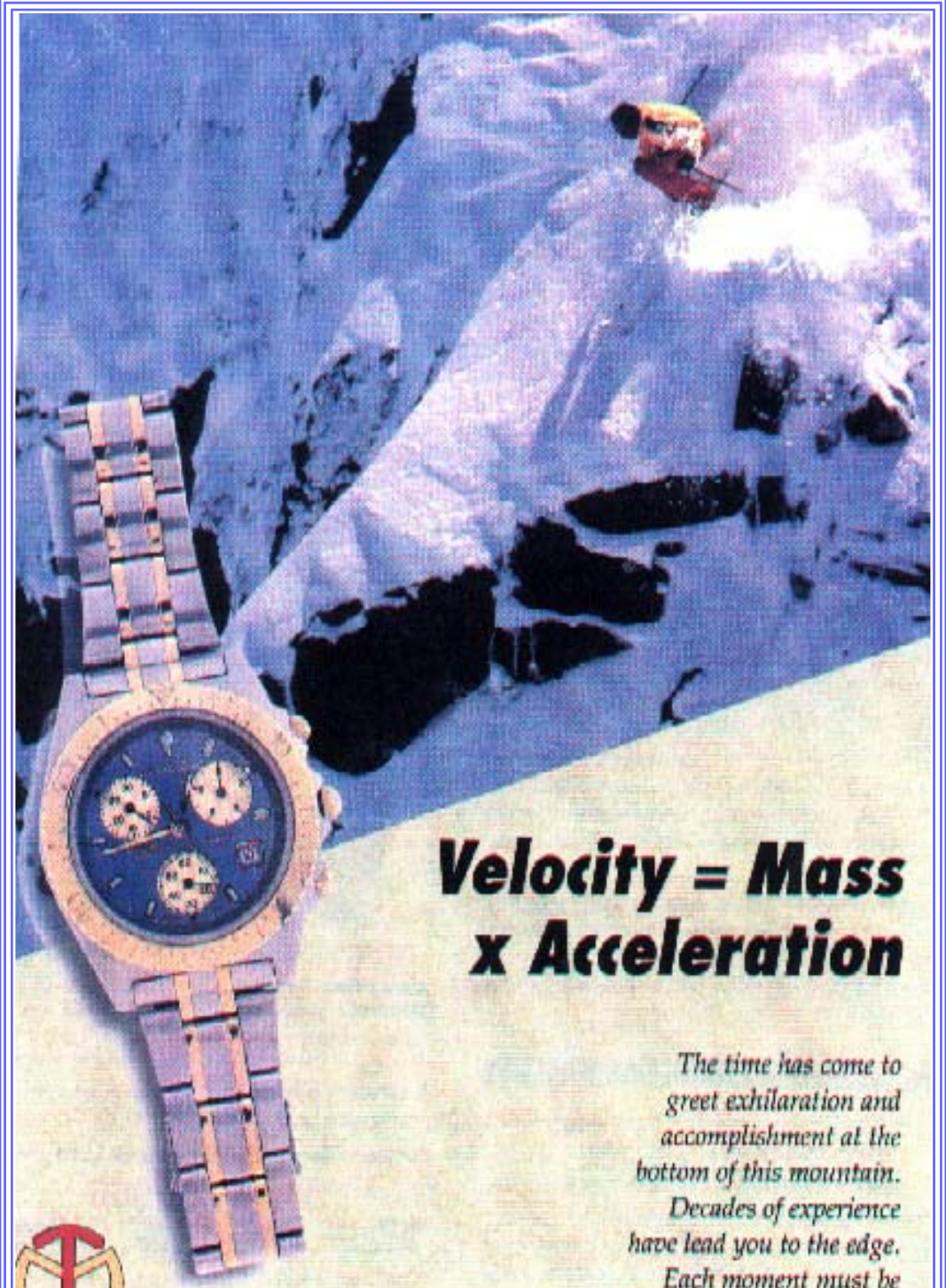
HST • WFPC2

PF95-14 · ST ScI OPO · April 5, 1995 · W. Couch (UNSW), NASA

Gravitational Lens
Galaxy Cluster 0024+1654
Hubble Space Telescope • WFPC2

Most of the universe is *dark* !

- Modified Newtonian dynamics



Velocity = Mass x Acceleration

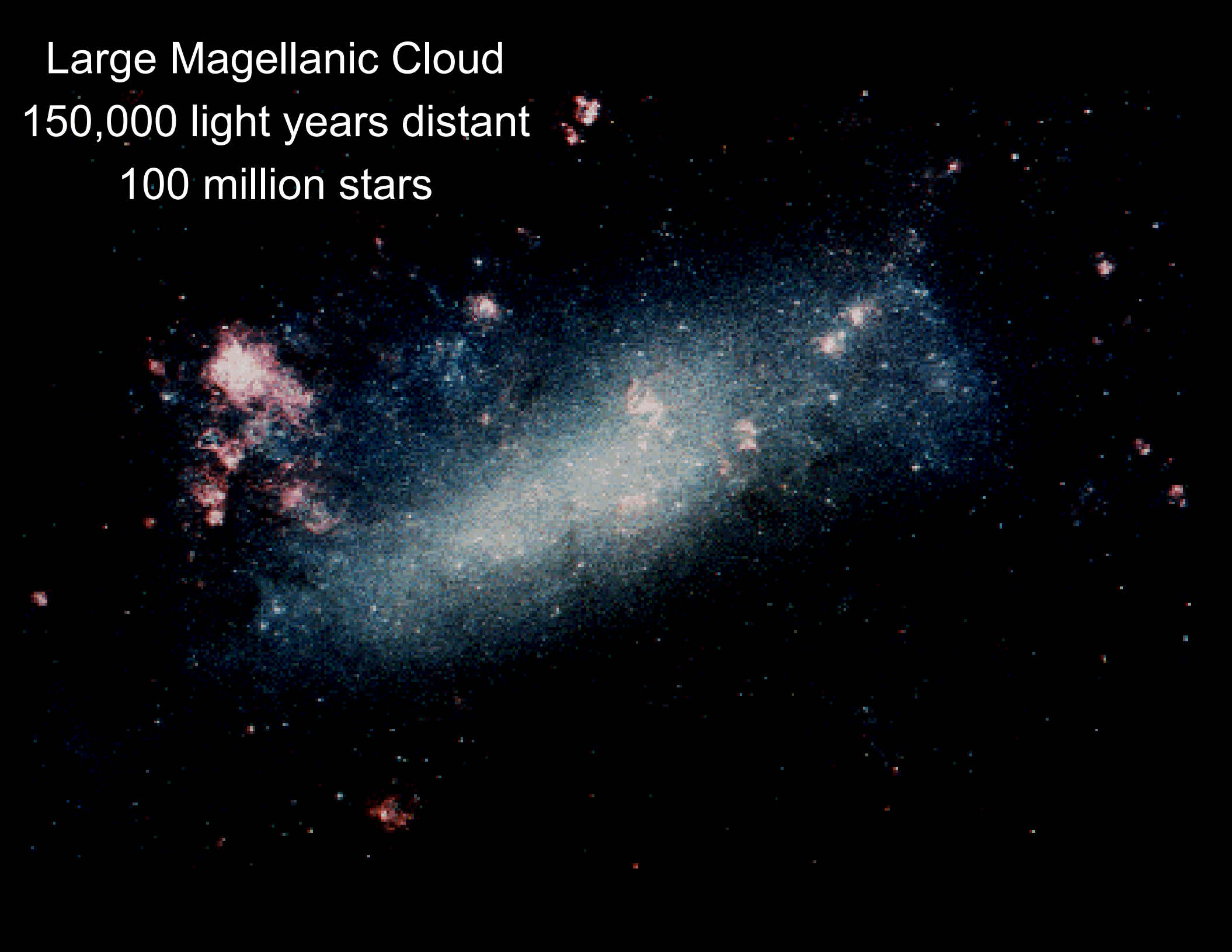
The time has come to greet exhilaration and accomplishment at the bottom of this mountain. Decades of experience have lead you to the edge. Each moment must be precise and confident. At this point there is one direction; forward.

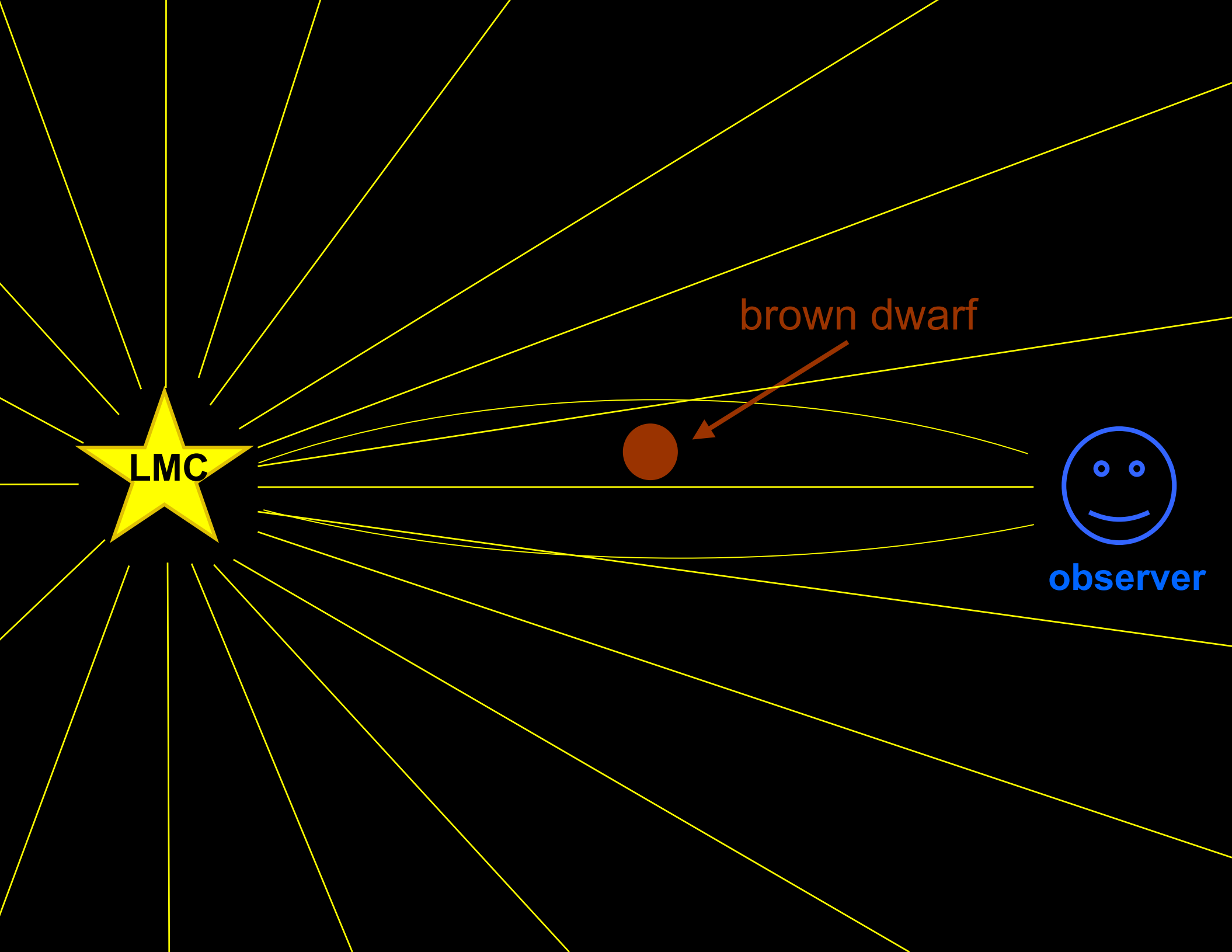
Mathey-Tissot®

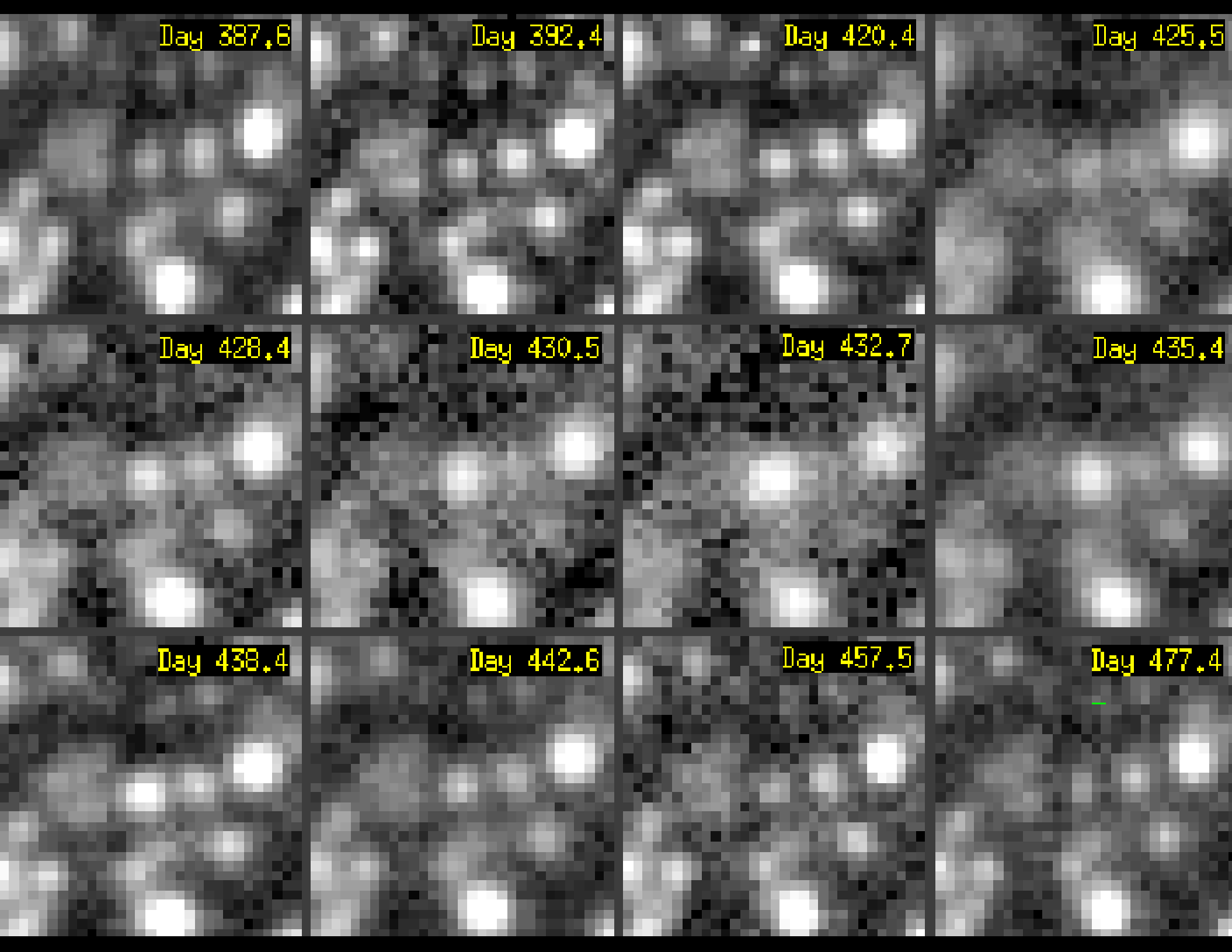
Most of the universe is *dark* !

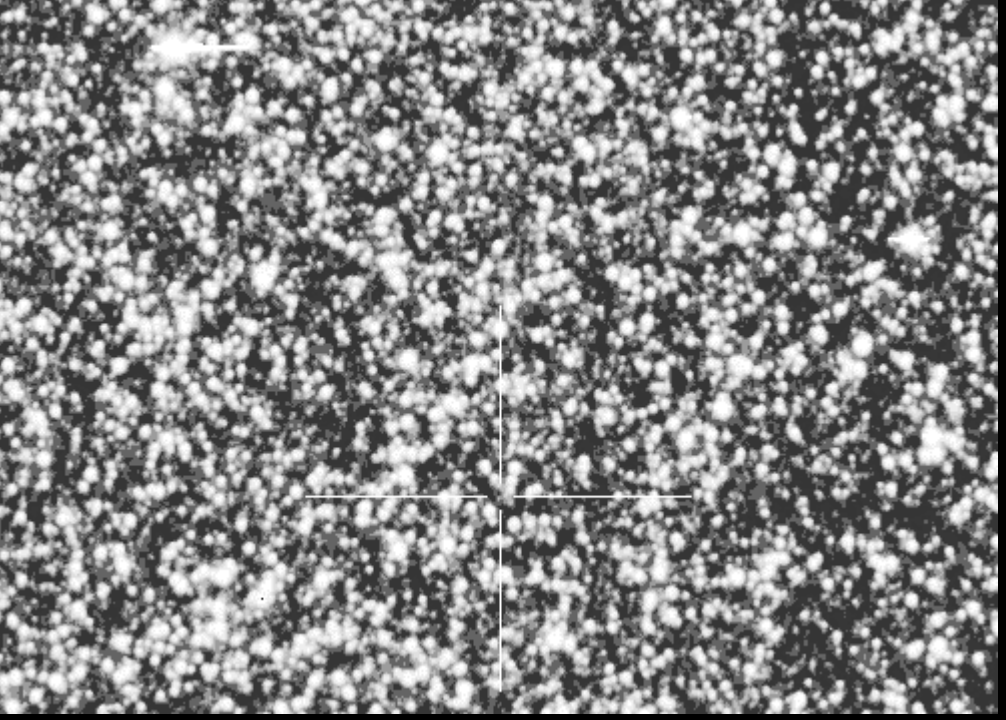
- Modified Newtonian dynamics
- Planets
- Mass disadvantaged stars

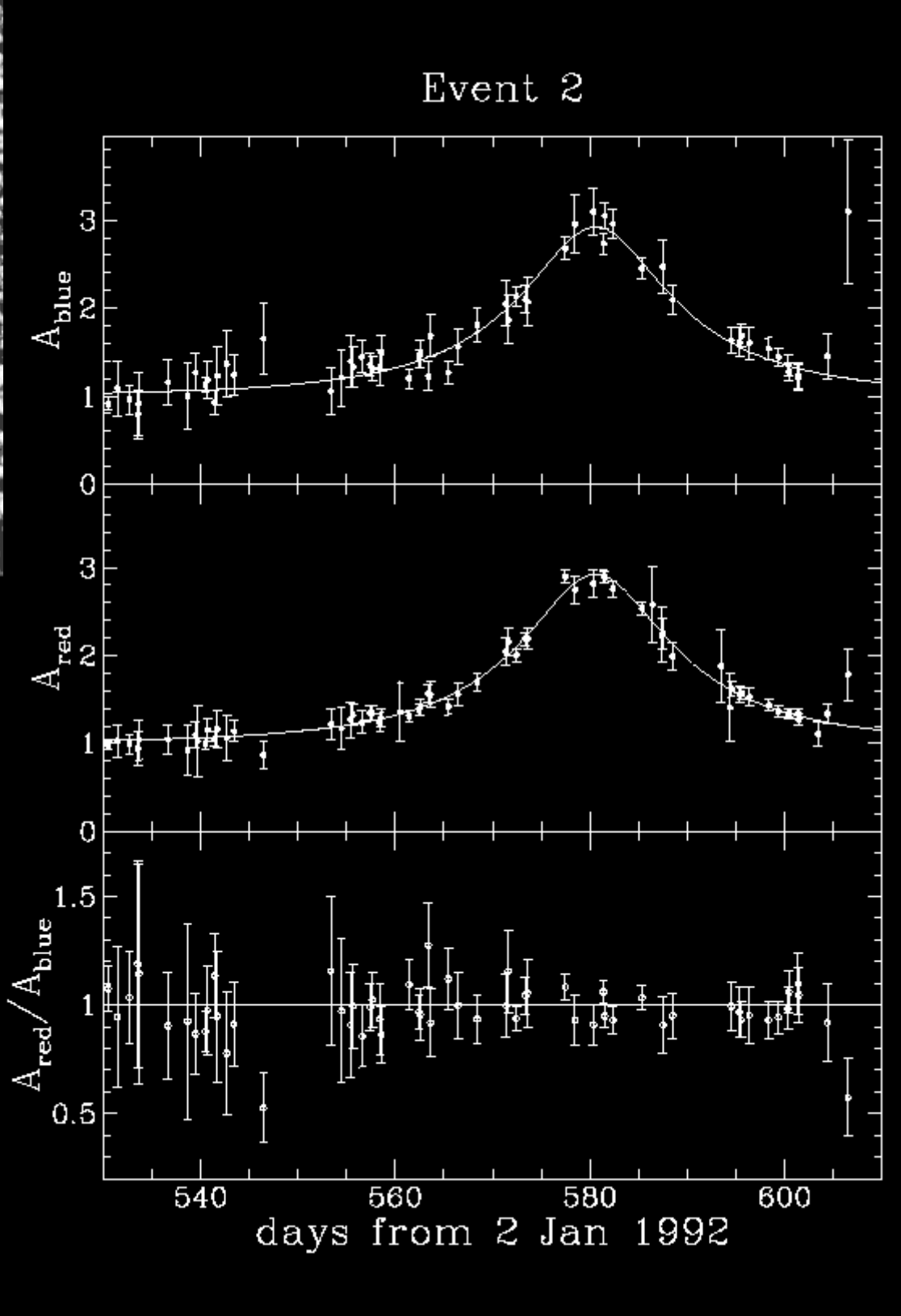
  brown red white
- Black holes


Large Magellanic Cloud
150,000 light years distant
100 million stars


brown dwarf
LMC
observer


Day 387.6
Day 392.4
Day 420.4
Day 425.5
Day 428.4
Day 430.5
Day 432.7
Day 435.4
Day 438.4
Day 442.6
Day 457.5
Day 477.4

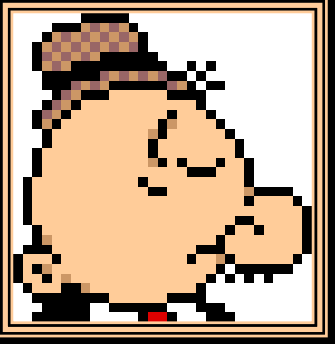



Event 2
A_{blue}
A_{red}
A_{red}/A_{blue}
0
1
2
3
0.5
1.5
540
560
580
600
days from 2 Jan 1992

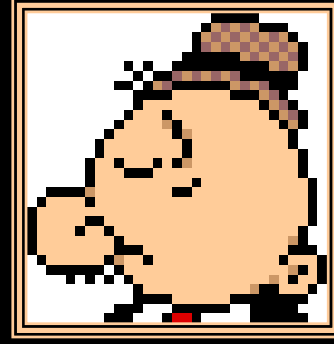
Most of the universe is *dark* !

- Modified Newtonian dynamics
- Planets
- Mass disadvantaged stars

  brown red white
- Black holes
- Fossil remnant of the big bang

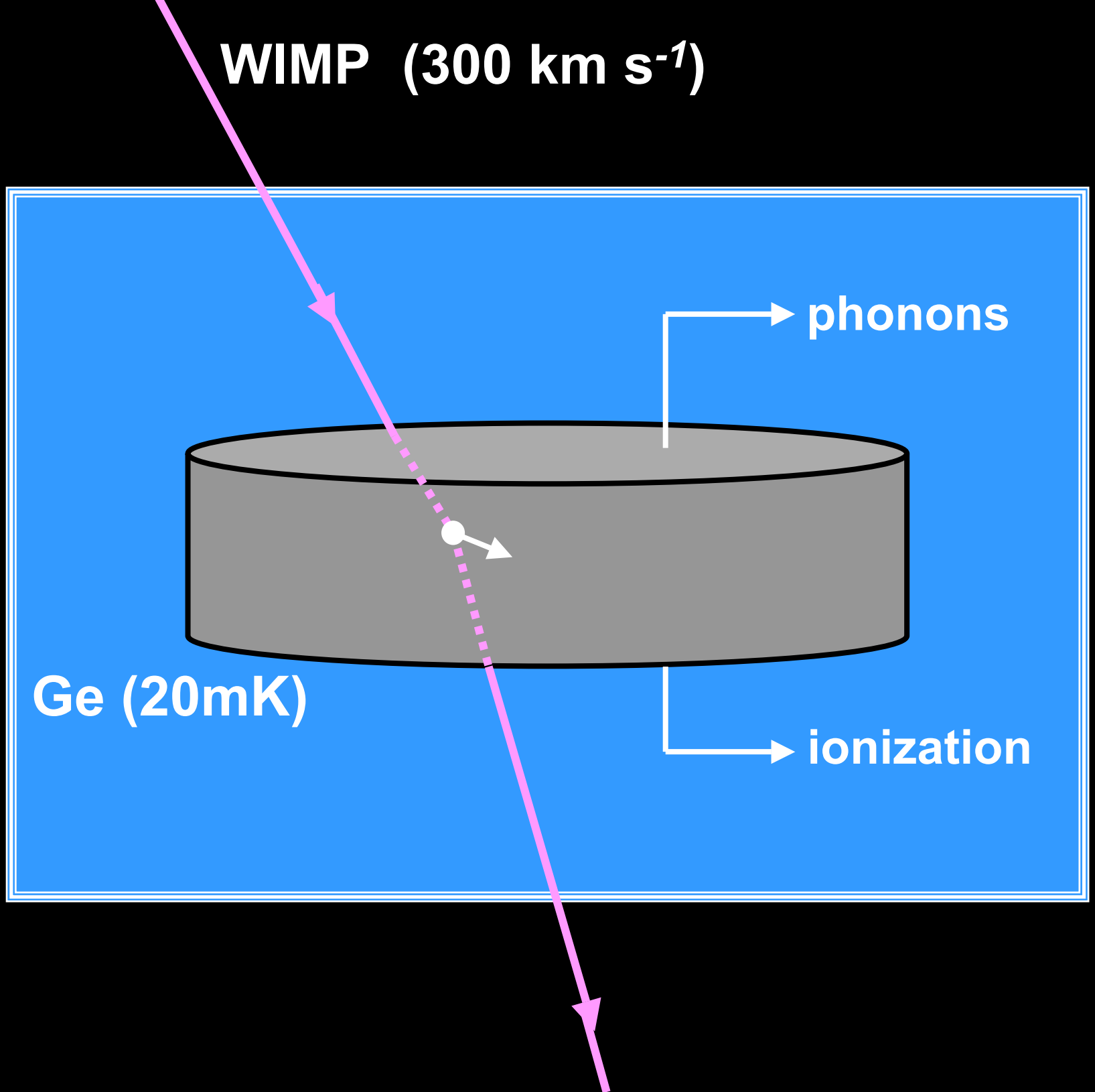


A WIMPY IDEA



- Most of the universe is *invisible*
- Dominated by the rest mass of an elementary particle
  - present in the primordial soup
  - massive
  - neutral
  - weakly interacting
  - slow
  - stable

WIMP

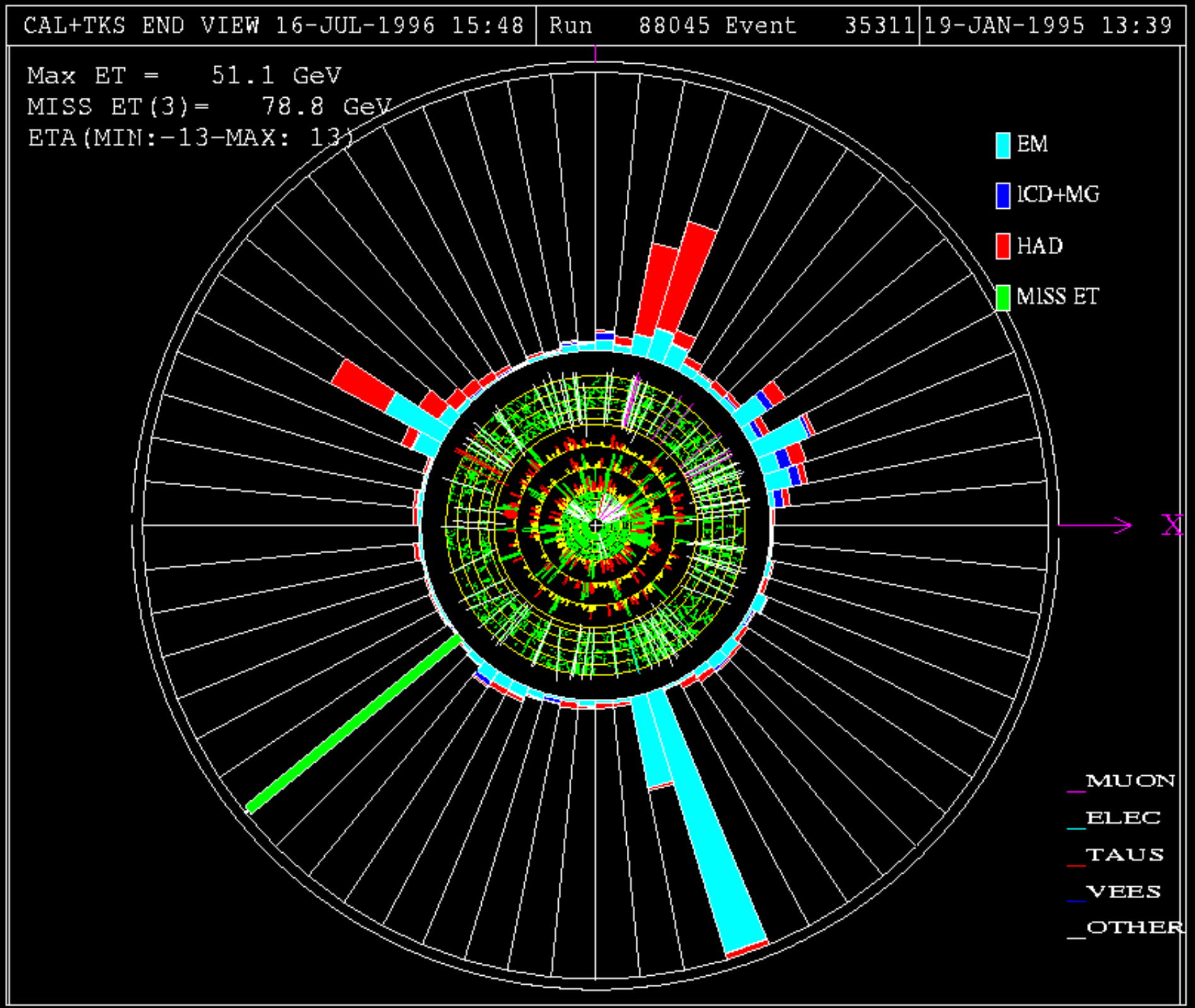

WIMP (300 km s-1)
phonons
Ge (20mK)
ionization

Desperately Seeking

SUSY

photons	⟷	photinos
selectrons	⟷	electrons
squarks	⟷	quarks
gravitons	⟷	gravitinos
wino	⟷	W

Lightest superpartner *stable!*

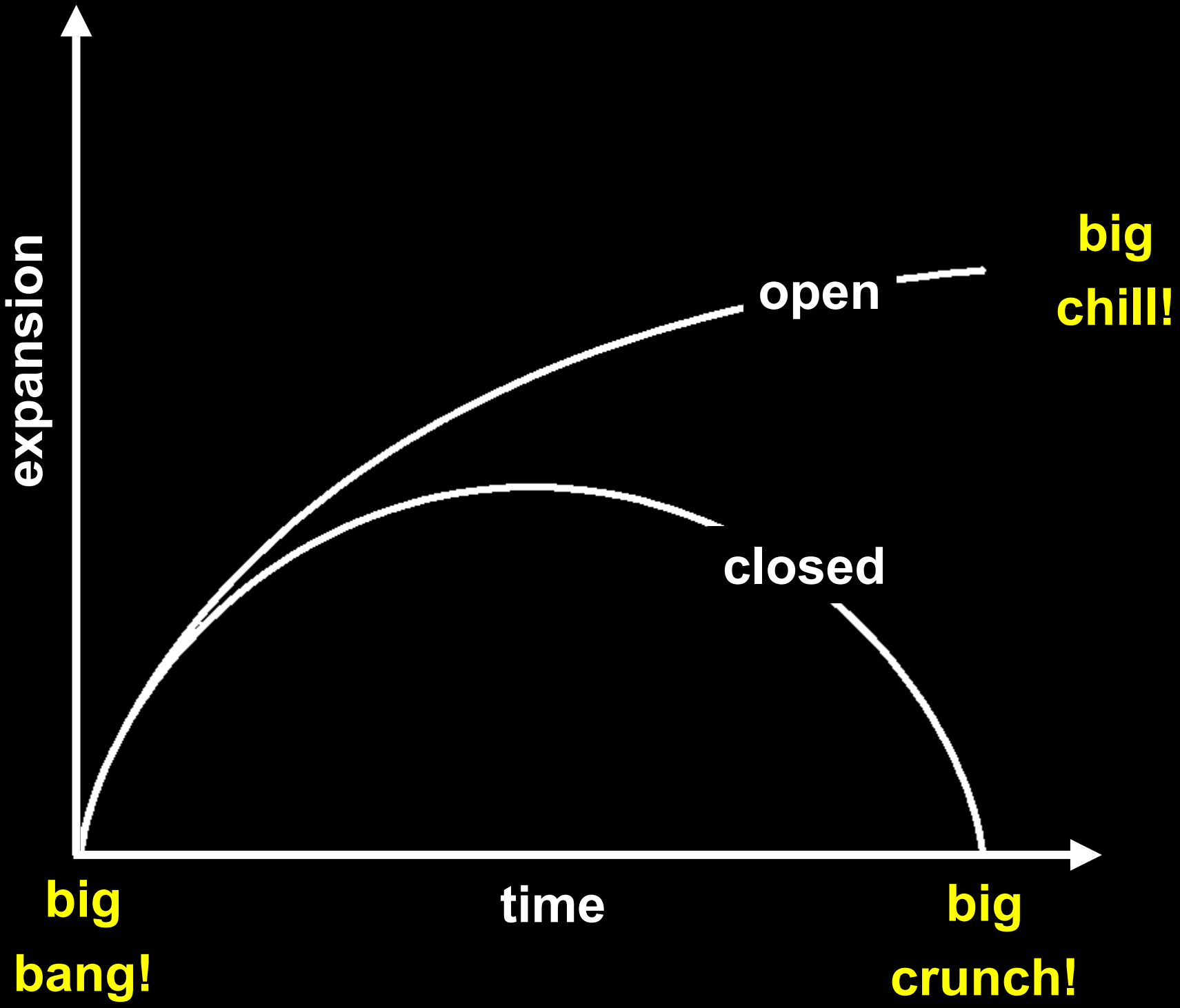

CAL+TKS END VIEW 16-JUL-1996 15:48
Run 88045 Event 35311
19-JAN-1995 13:39
Max ET = 51.1 GeV
MISS ET(3)= 78.8 GeV
ETA(MIN:-13-MAX: 13)
EM
lCD+MG
HAD
MISS ET
X
MUON
ELEC
TAUS
VEES
OTHER

MINOS

also CERN → Gran Sasso


the Neutrinos
Ballard Firehouse
January 26
February 9
$3.00

The ultimate fate of the universe

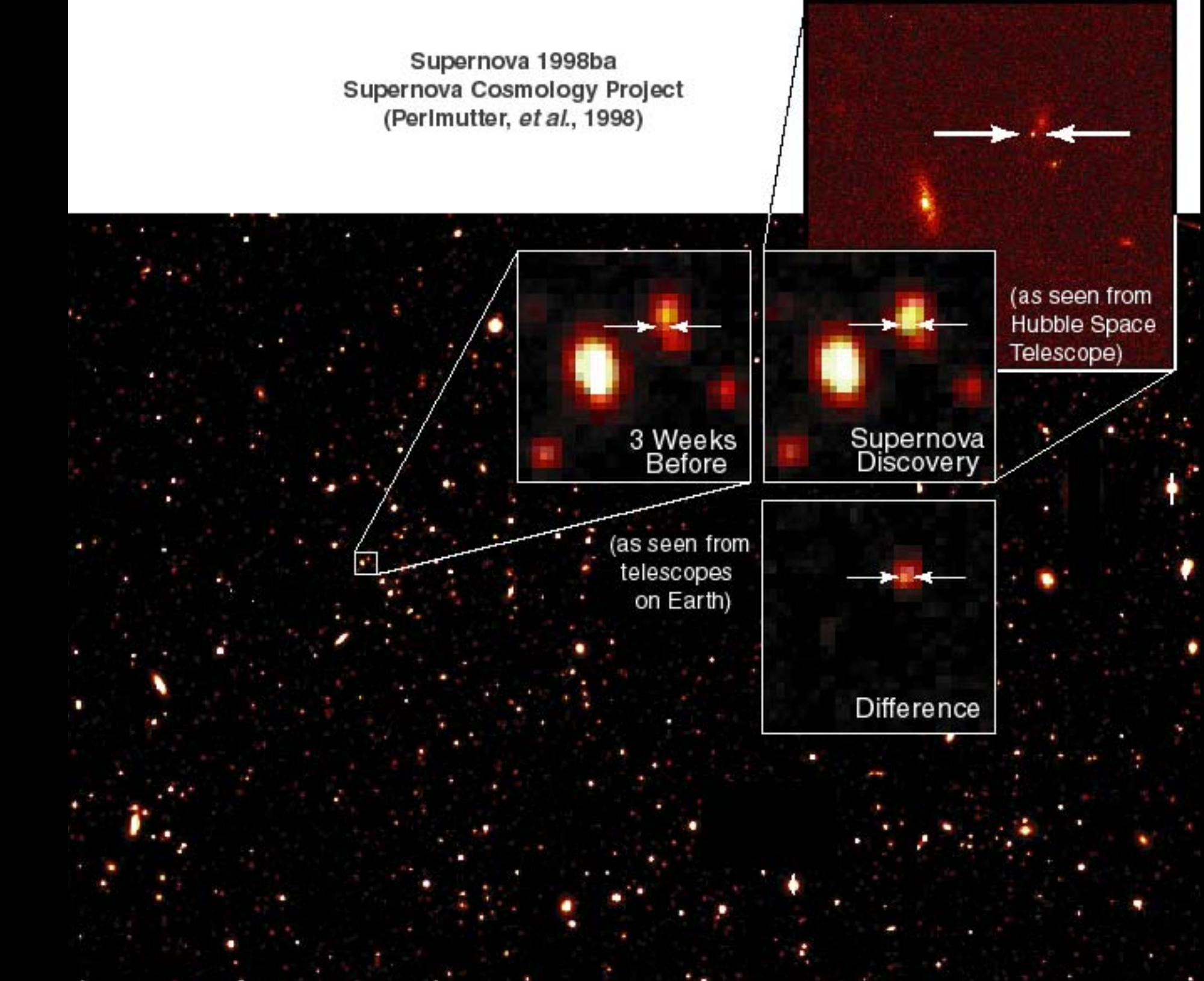


Most of the universe is *dark* !

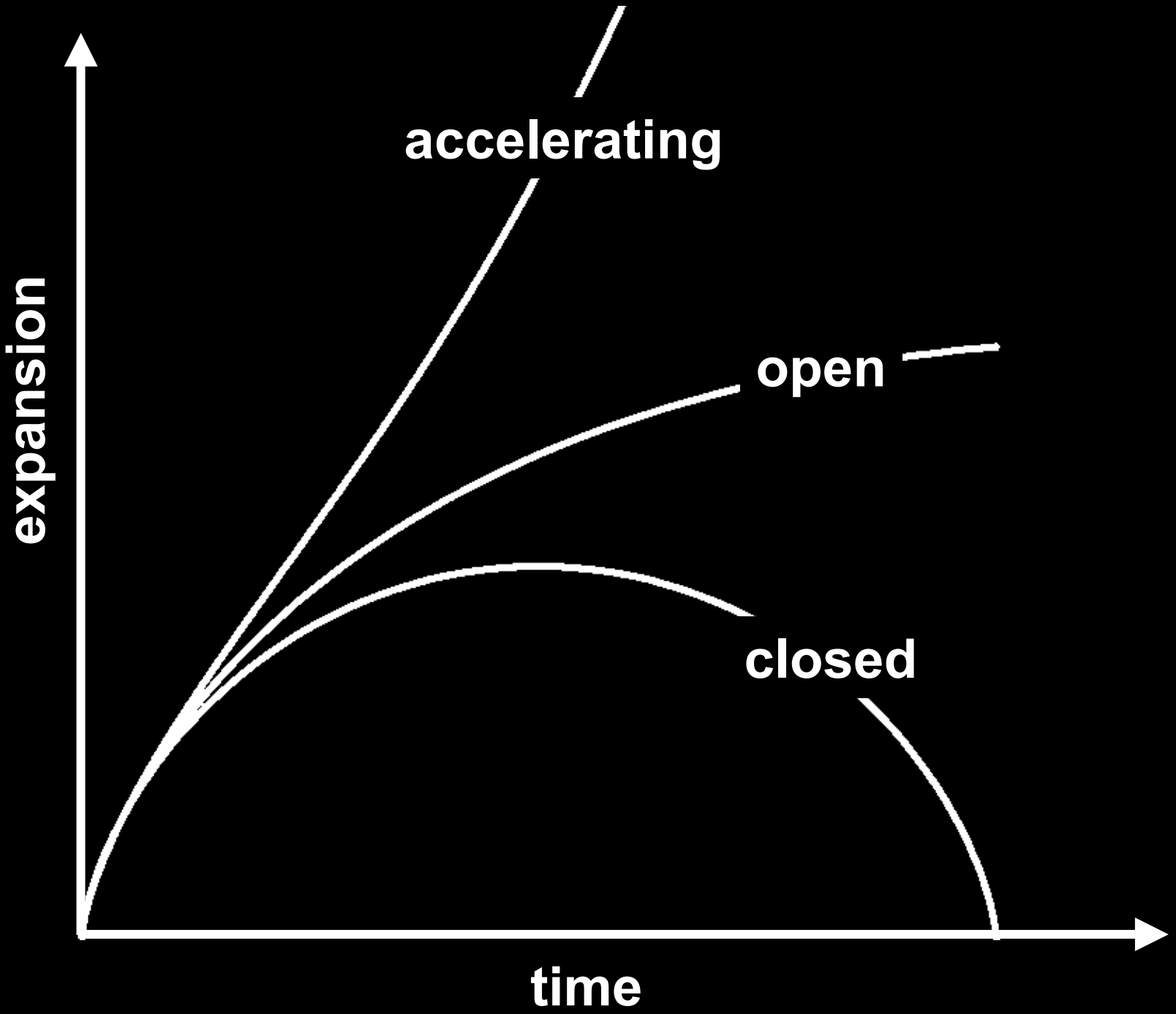
- Modified Newtonian dynamics
- Planets
- Mass disadvantaged stars

  brown red white
- Black holes
- Fossil remnant of the big bang
- The weight of space


© Anglo-Australian Observatory
Supernova 1987A in the Large Magellanic Cloud


Supernova 1998ba
Supernova Cosmology Project
(Perlmutter, *et al.*, 1998)
(as seen from Hubble Space Telescope)
3 Weeks Before
Supernova Discovery
(as seen from telescopes on Earth)
Difference

The accelerating universe?



The accelerating universe?

- Normal matter slows the expansion of the universe (deceleration). Gravity is attractive.

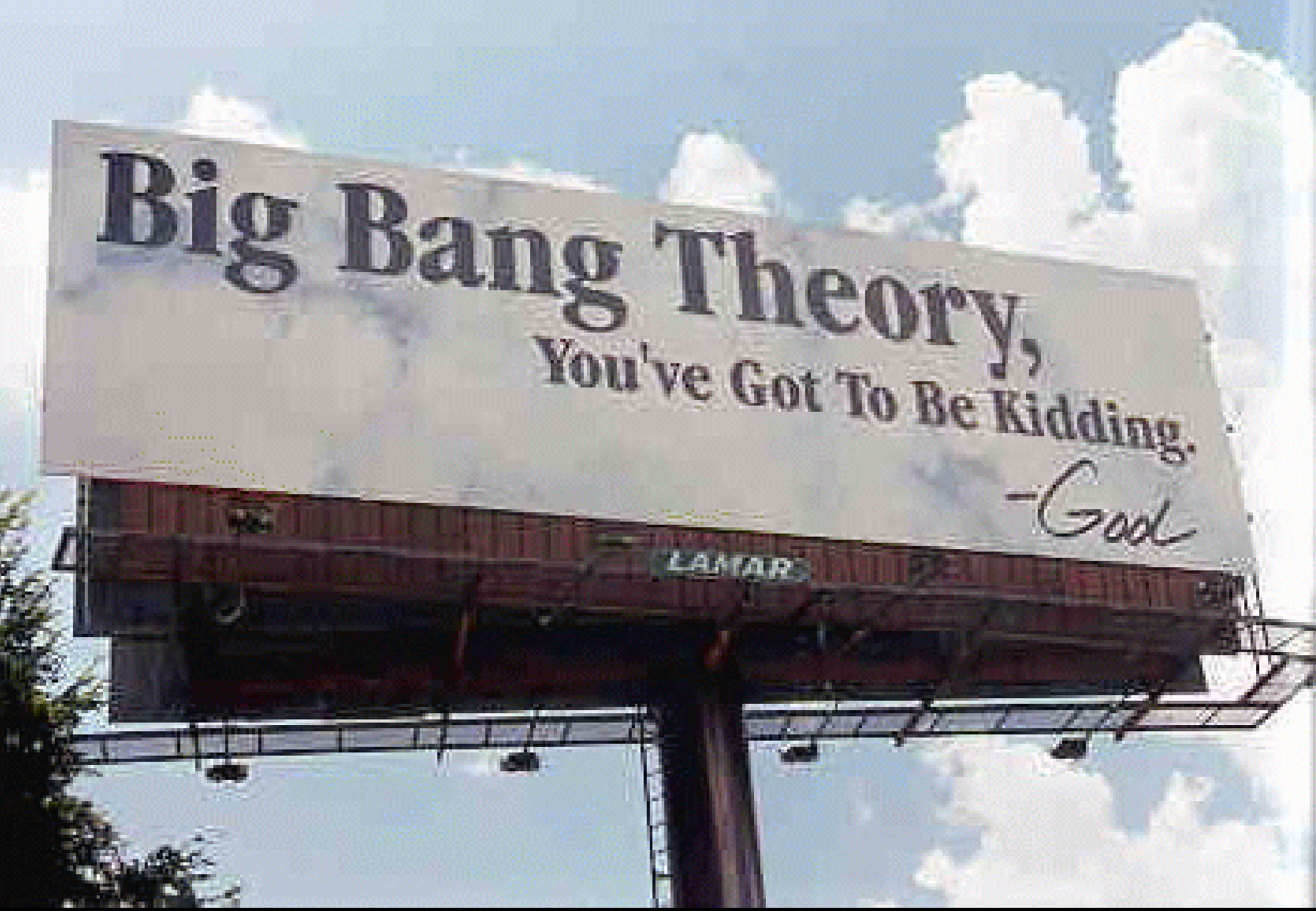
$$\text{acceleration} = -G \times (\text{Mass} + \text{pressure})$$

Newton — Mass

Einstein — pressure

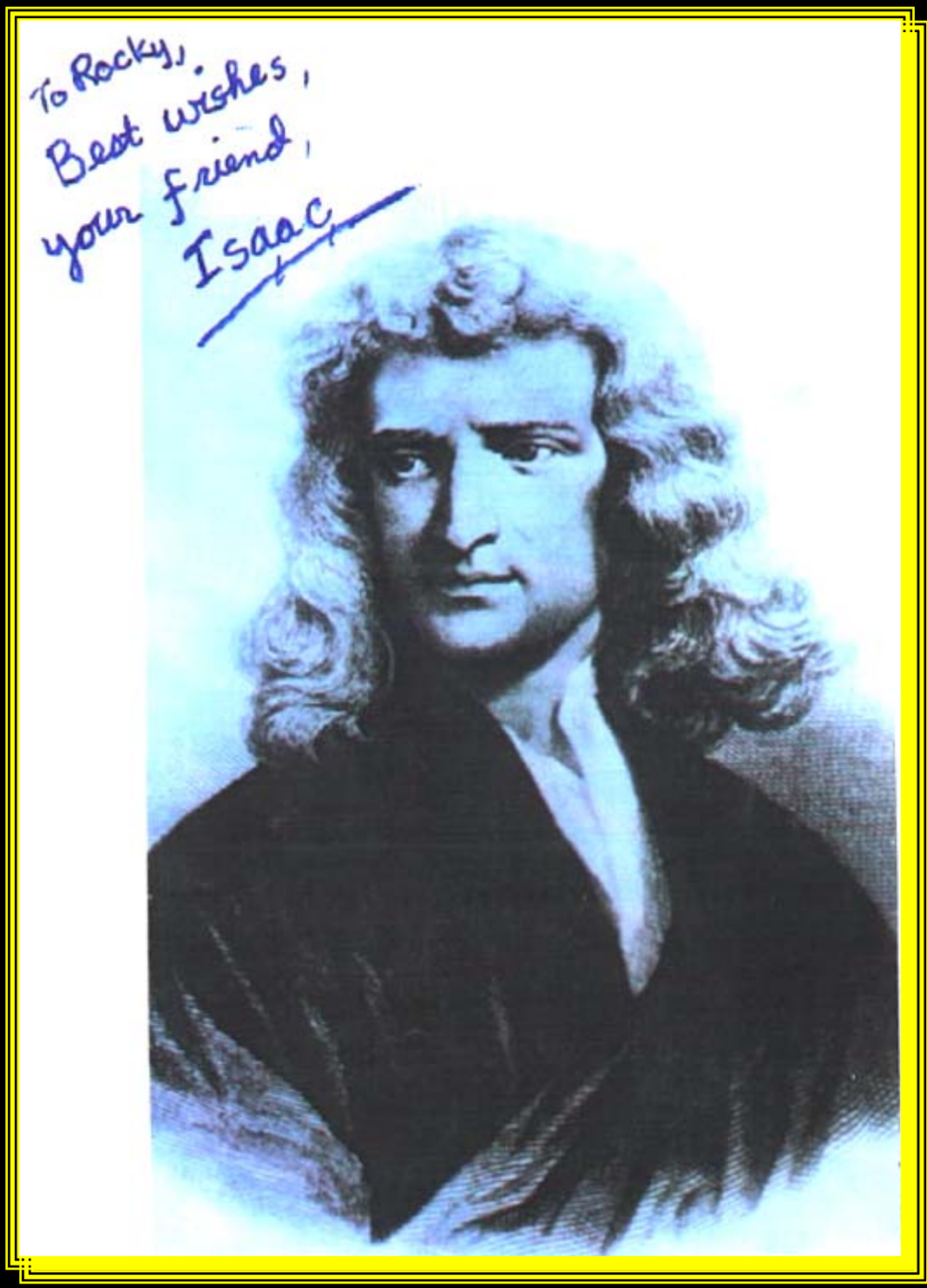
- Negative pressure would push apart space.

- "Vacuum energy" (the mass-energy density of space) is positive, but its pressure is *negative.*


Big Bang Theory,
You've Got To Be Kidding.
-God
LAMAR

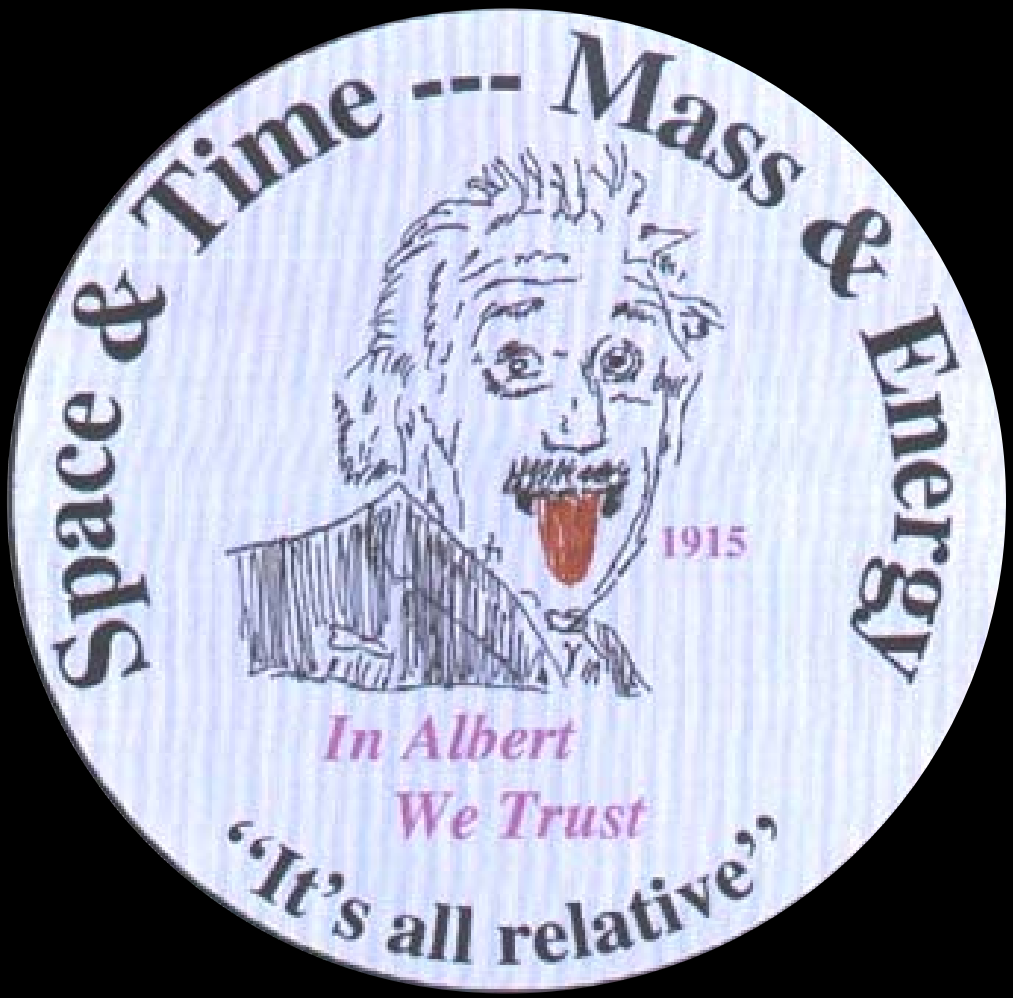
Absolute space,
in its own nature,
without relation
to anything external,
remains always similar
and immovable.

Isaac Newton
1686
Principia



Space and time
are related.

Albert Einstein
1905



Space is dynamical
(curved, warped, bent,
etc.).

Albert Einstein
1915

Space expands.

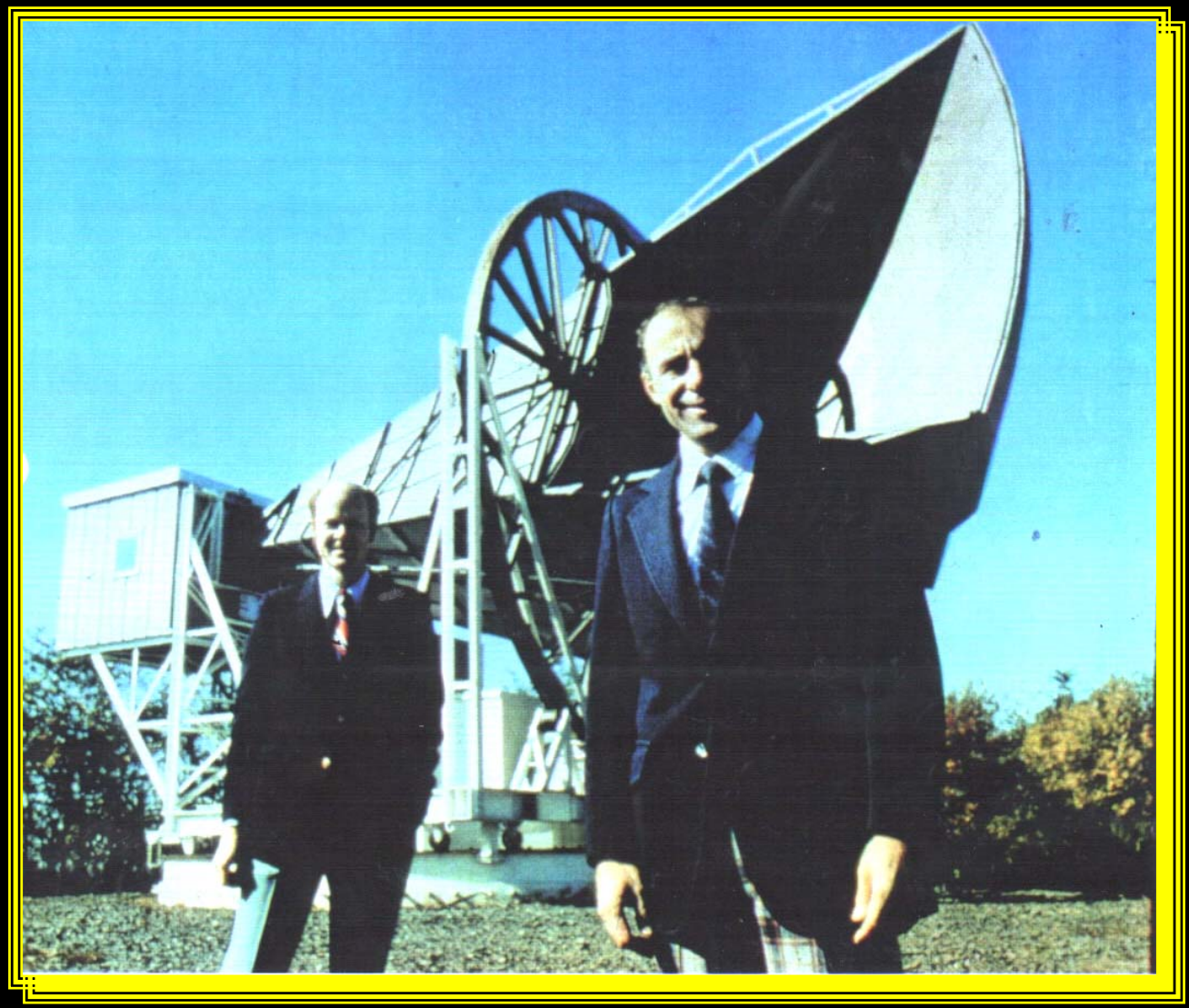
Edwin Hubble
1929

The University of Chicago

1909 National Champions

The universe
is hot.

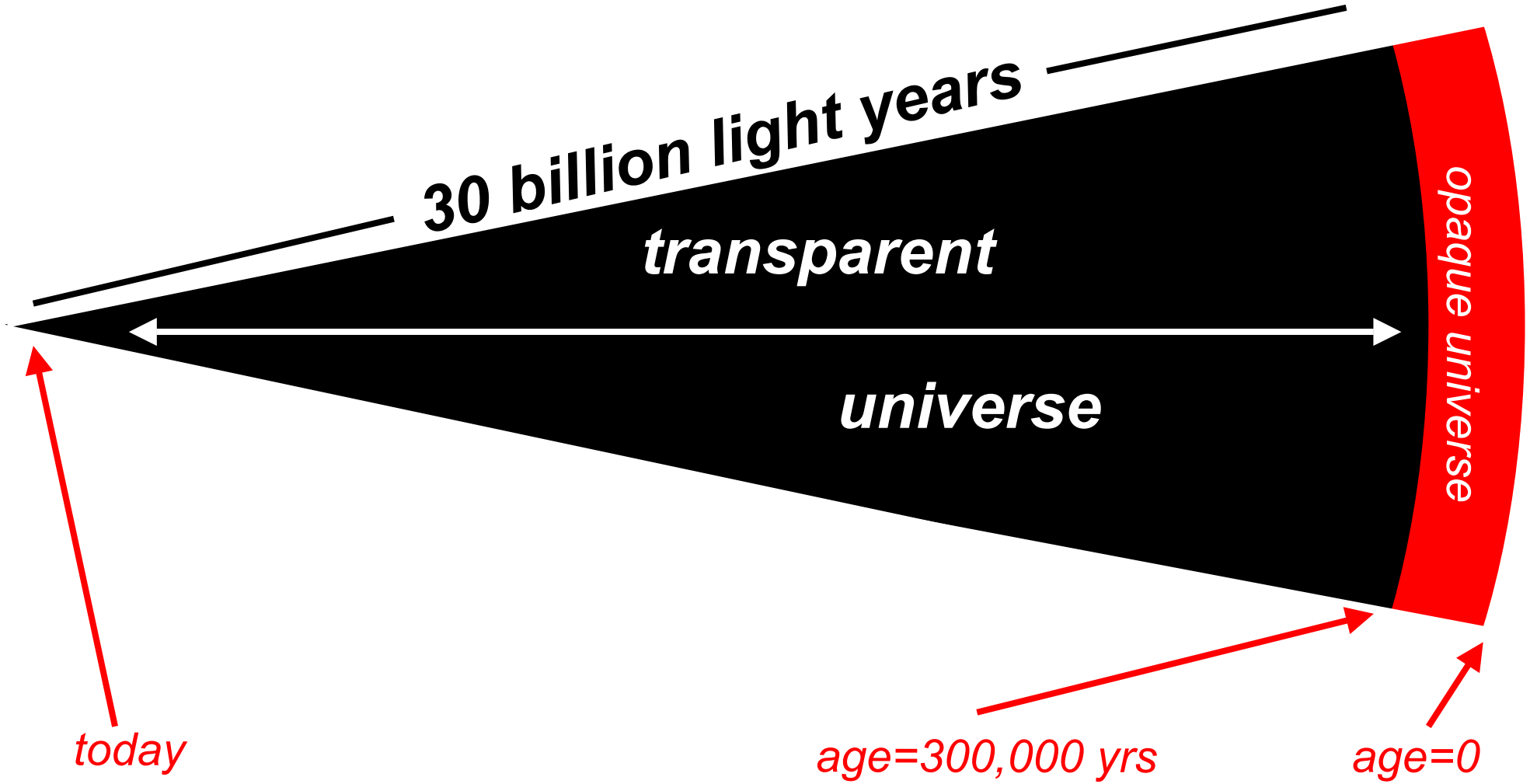
Arno Penzias
Robert Wilson
1965

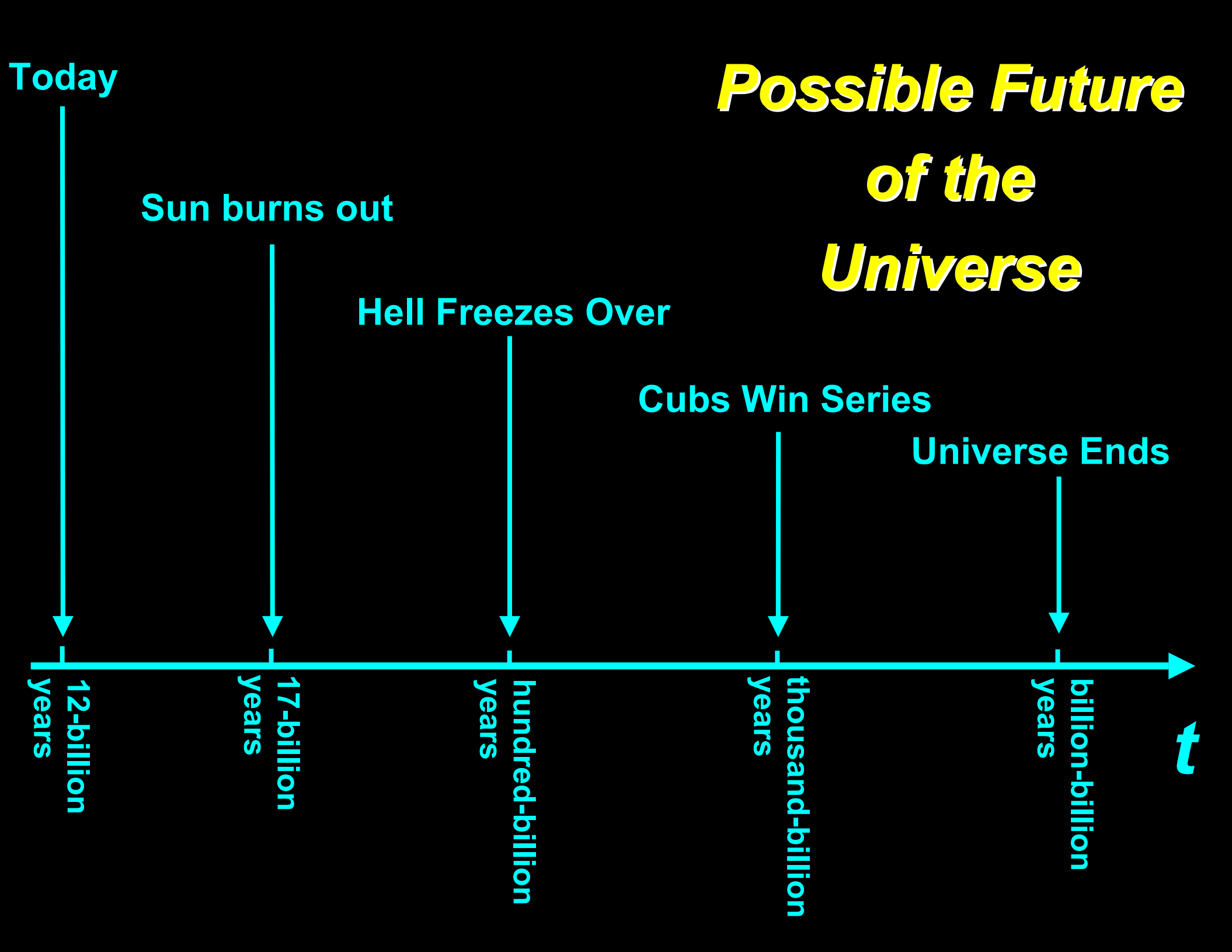


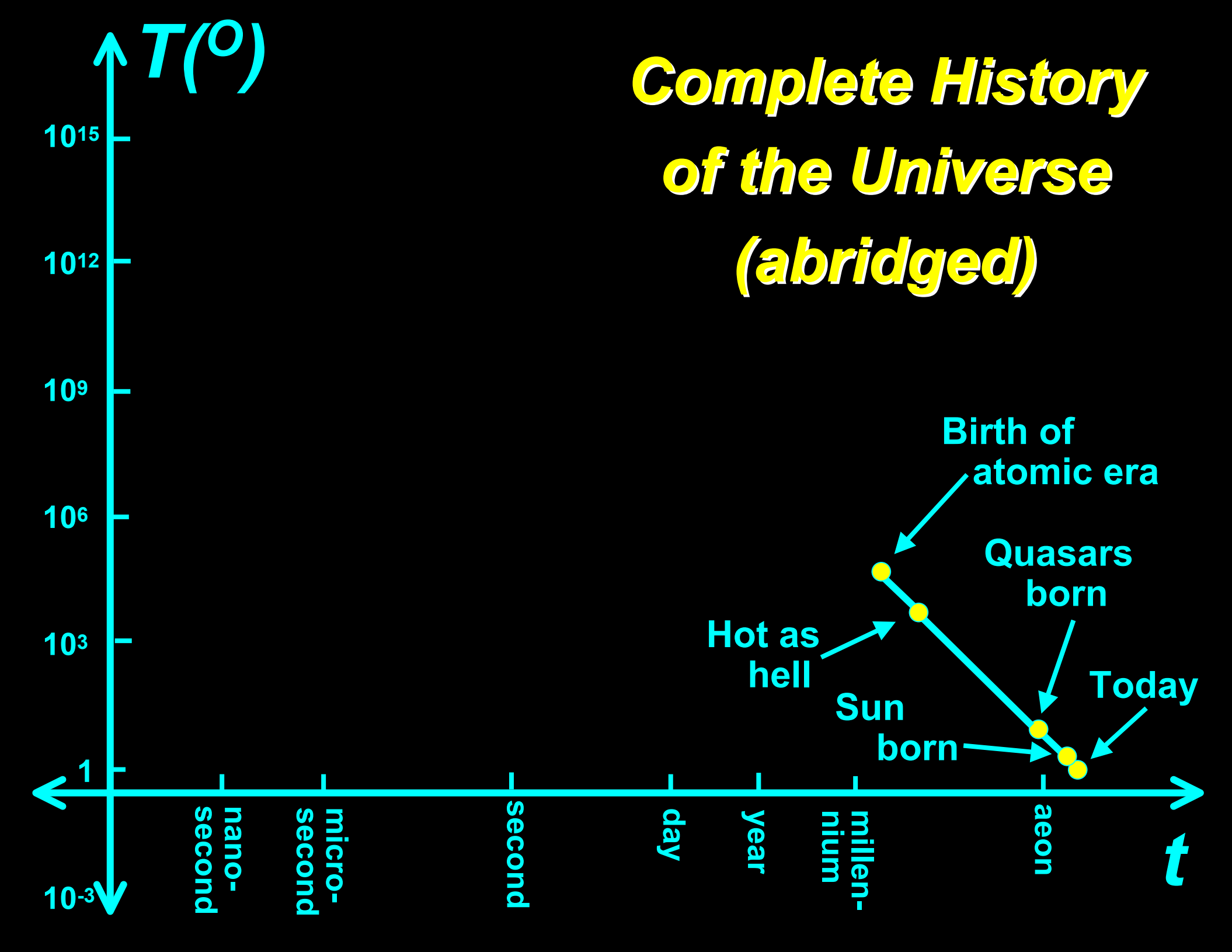
BACKGROUND RADIATION

T = 3K = - 454 F = - 270 C

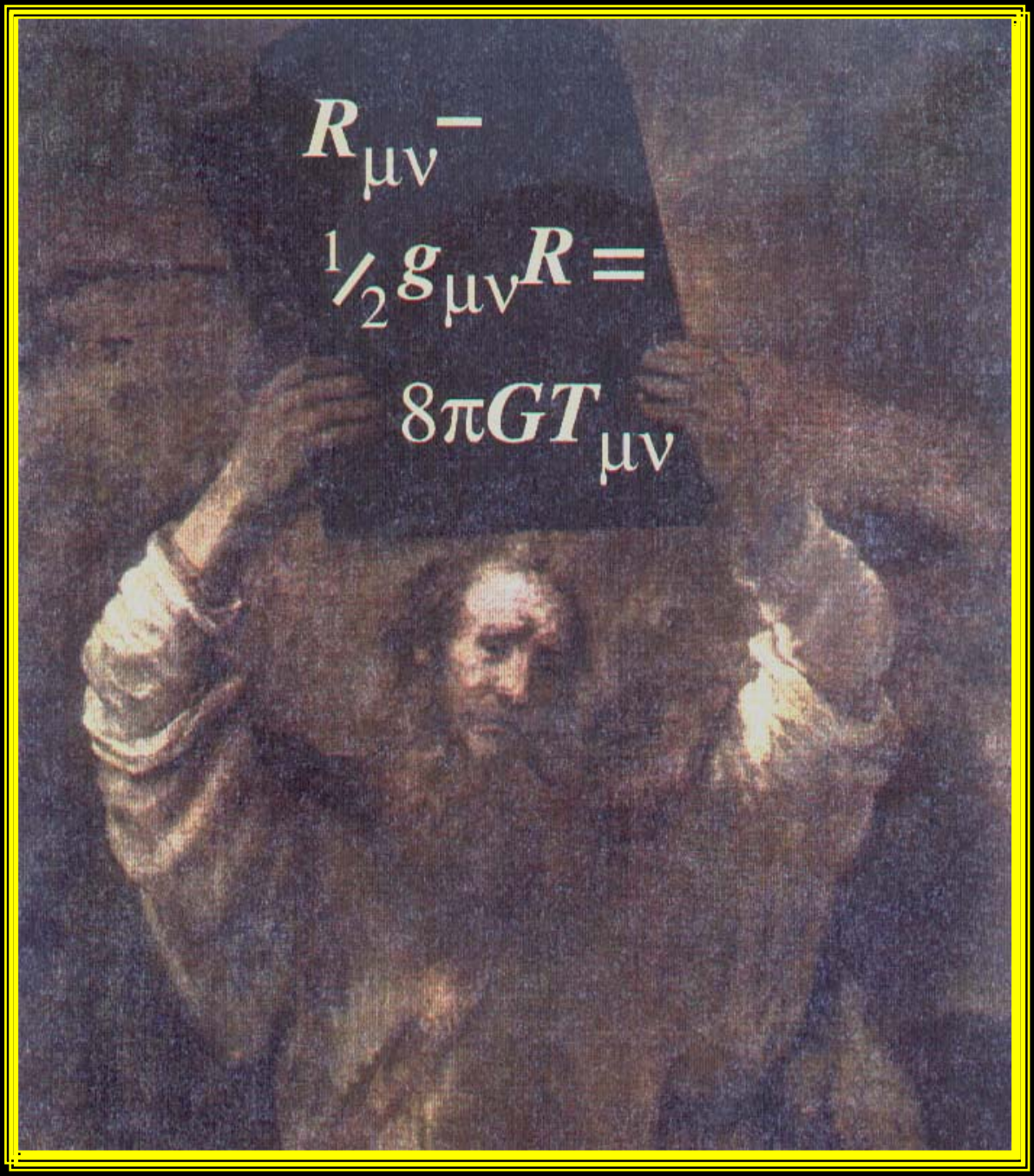
Cosmic Background Radiation



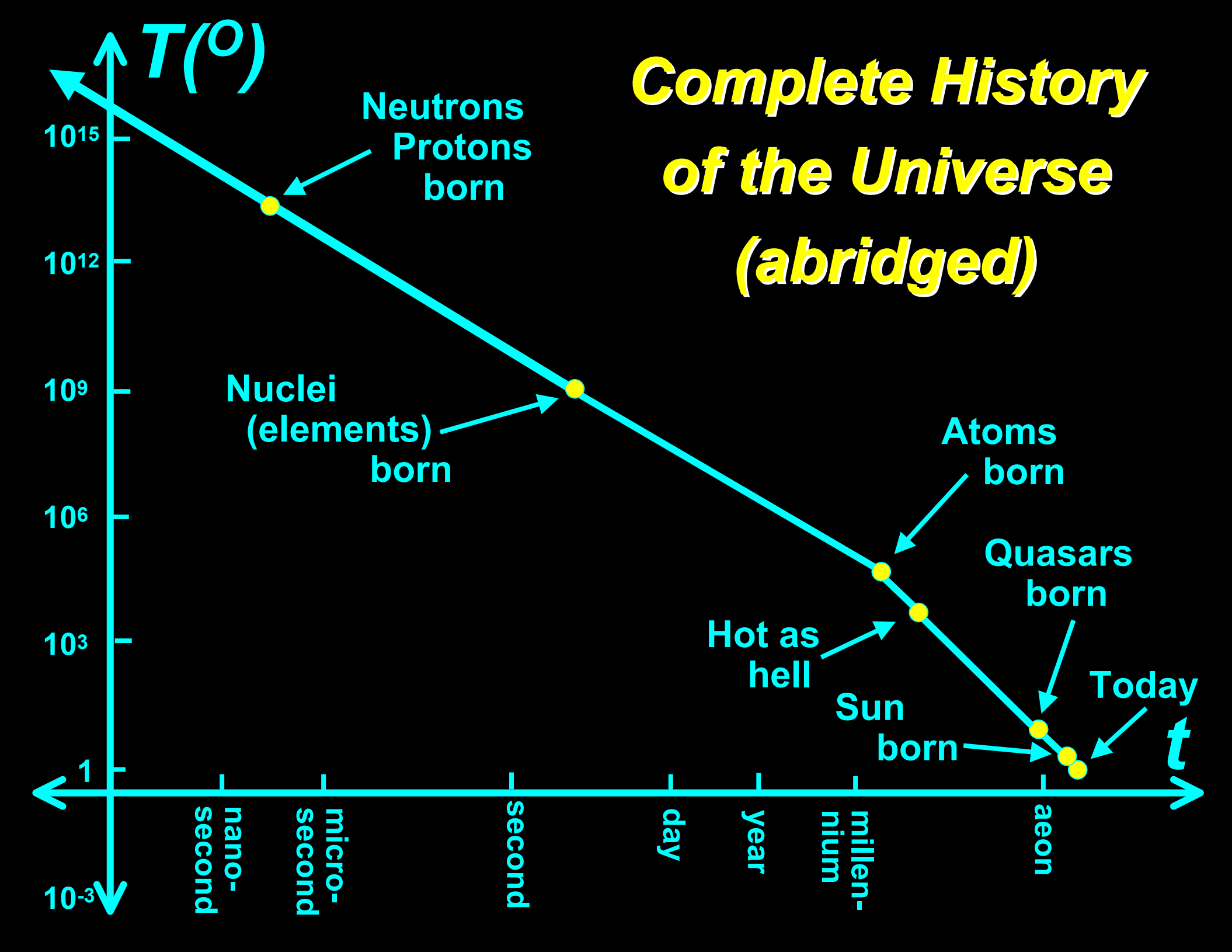

Possible Future of the Universe
Today
Sun burns out
Hell Freezes Over
Cubs Win Series
Universe Ends
12-billion years
17-billion years
hundred-billion years
thousand-billion years
billion-billion years
t


T(°)
Complete History of the Universe (abridged)
10^15
10^12
10^9
10^6
10^3
1
10^-3
Birth of atomic era
Quasars born
Hot as hell
Today
Sun born
nano-second
micro-second
second
day
year
millen-nium
aeon
t

Modern Laws of Genesis



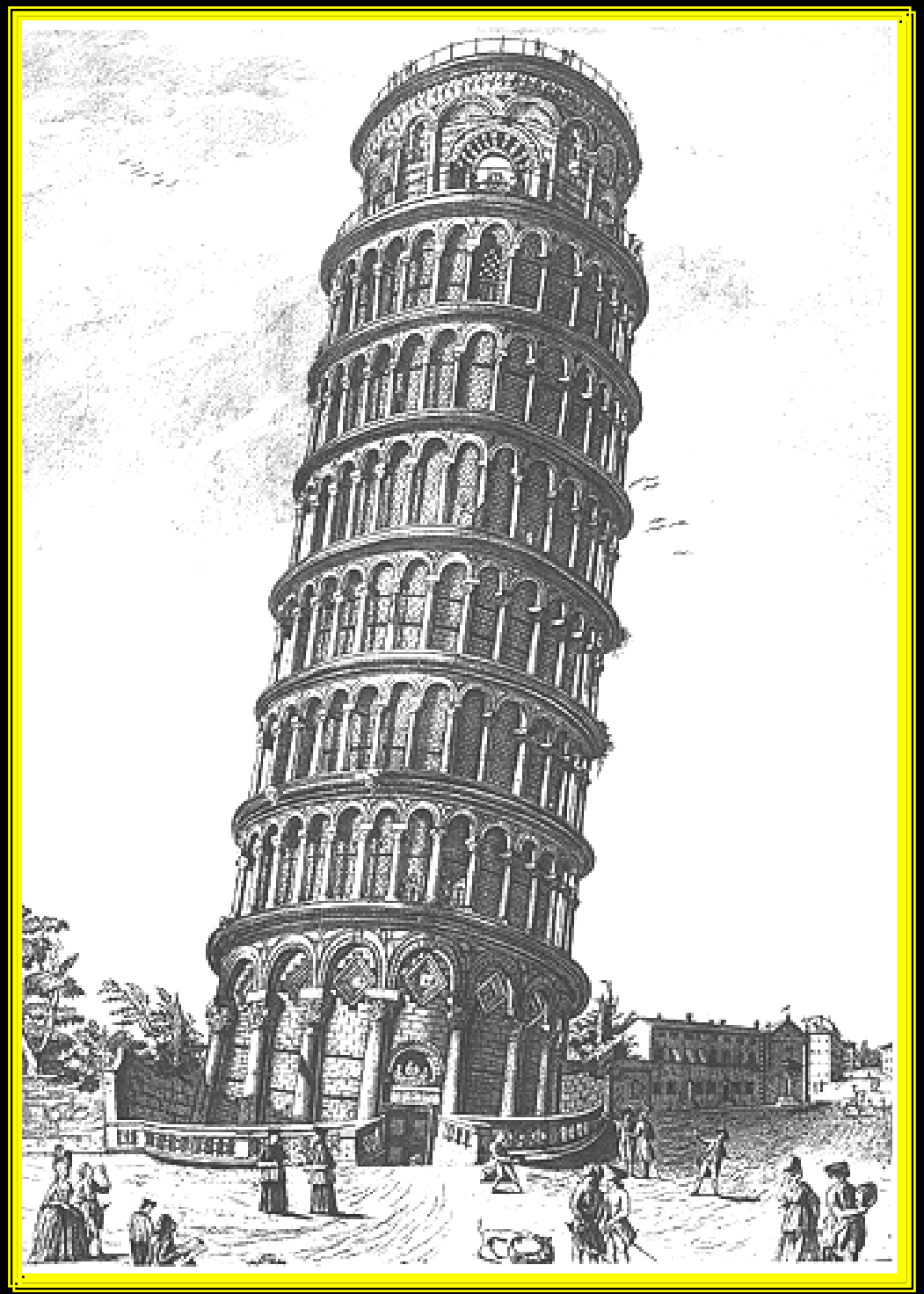
(10 nonlinear partial differential equations)


T(°)
Complete History of the Universe (abridged)
Neutrons Protons born
Nuclei (elements) born
Atoms born
Quasars born
Hot as hell
Sun born
Today
t
10^15
10^12
10^9
10^6
10^3
1
10^-3
nano-second
micro-second
second
day
year
millen-nium
aeon

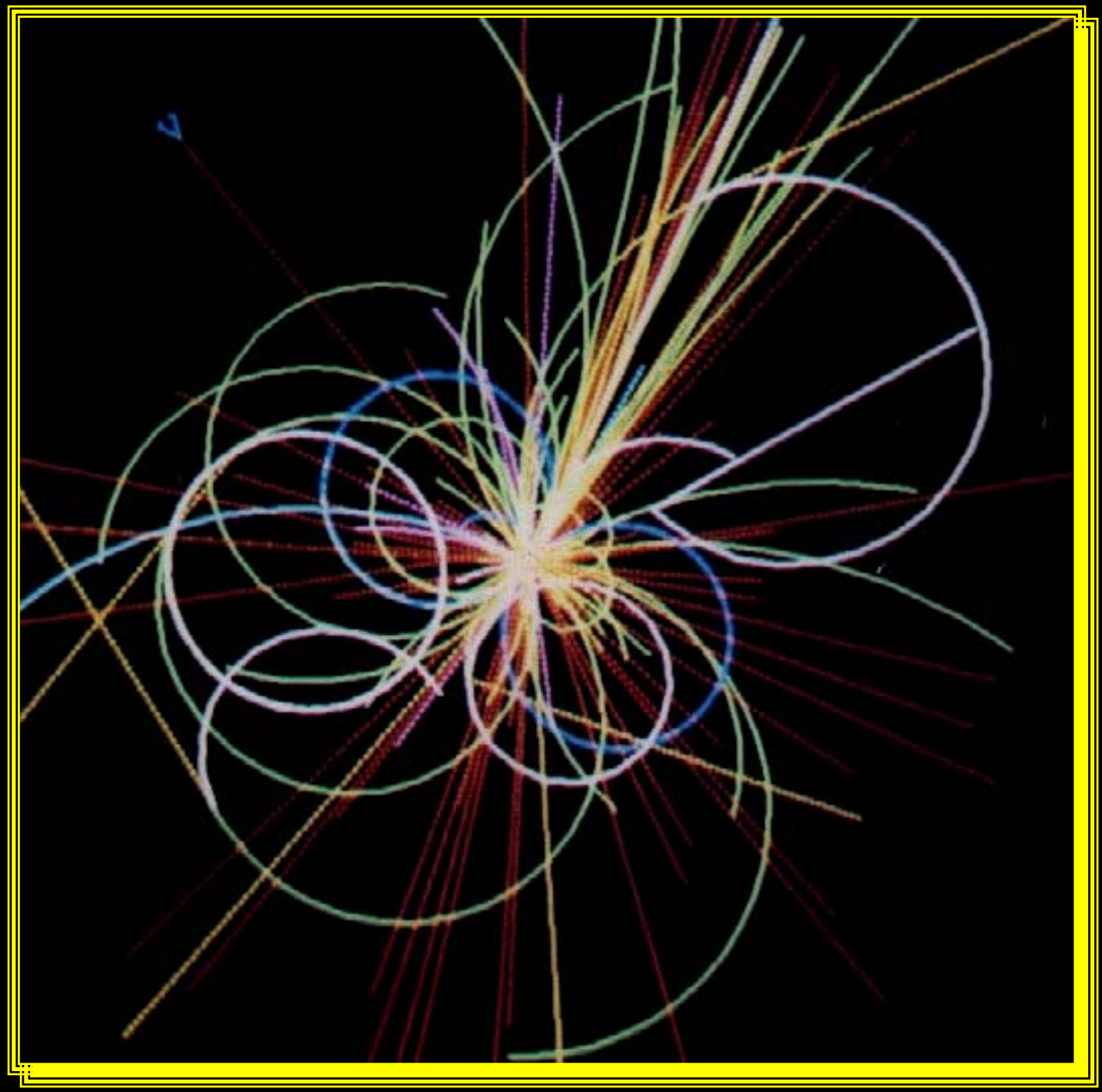
Fermi National Accelerator Laboratory

Particle Accelerator-Telescope-Time Machine

Galileo Pisan Accelerator Laboratory

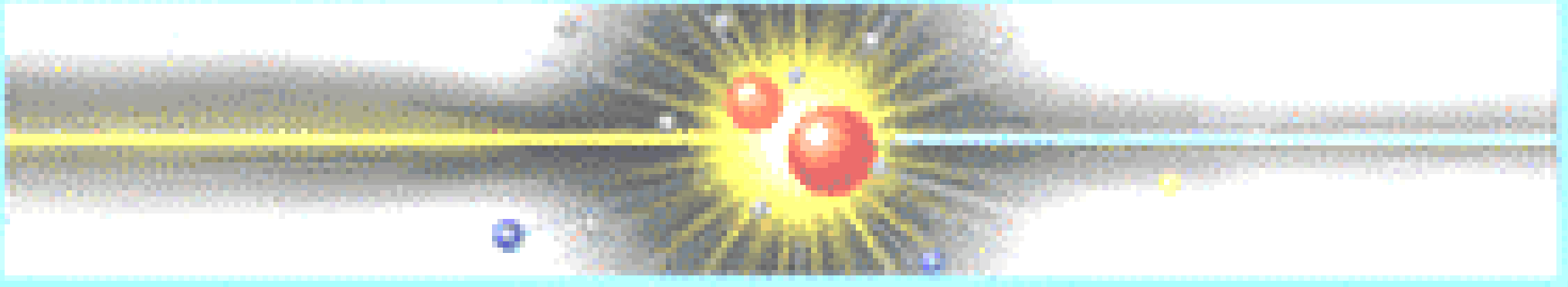


FERMILAB PRIMORDIAL SOUP




Fermilabs
Primordial
SOUP

FERMILAB PRIMORDIAL SOUP



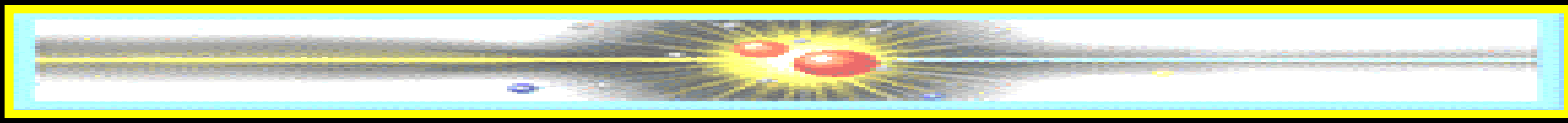
$3X10^{15}$ degrees

3,000,000,000,000,000°

$4X10^{-12}$ seconds

0.000 000 000 004 seconds

FERMILAB PRIMORDIAL SOUP



Caution !!!

CONDENSED

50 Earth masses in matter
50 Earth masses in antimatter
\+ extra mountain of matter

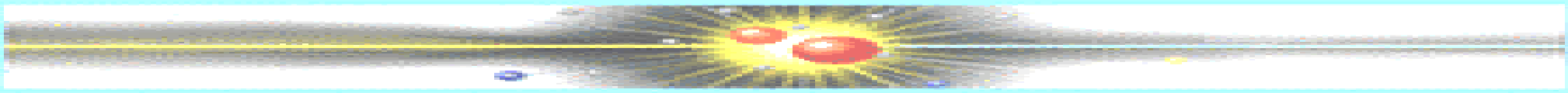
HOT

64 billion years of energy output of sun

CONTENTS

elementary particles and antiparticles

FERMILAB PRIMORDIAL SOUP



KNOWN INGREDIENTS:

56% QUARKS
16% GLUONS (STRONG FORCE)
9% ELECTRON-LIKE PARTICLES
9% W's AND Z's (WEAK FORCE)
5% NEUTRINOS
2% PHOTONS (ELECTROMAGNETIC FORCE)
2% GRAVITONS (GRAVITATIONAL FORCE)
1% HIGGS BOSONS

SECRET INGREDIENT:

DARK MATTER

300,000 years

atoms form

3 minutes

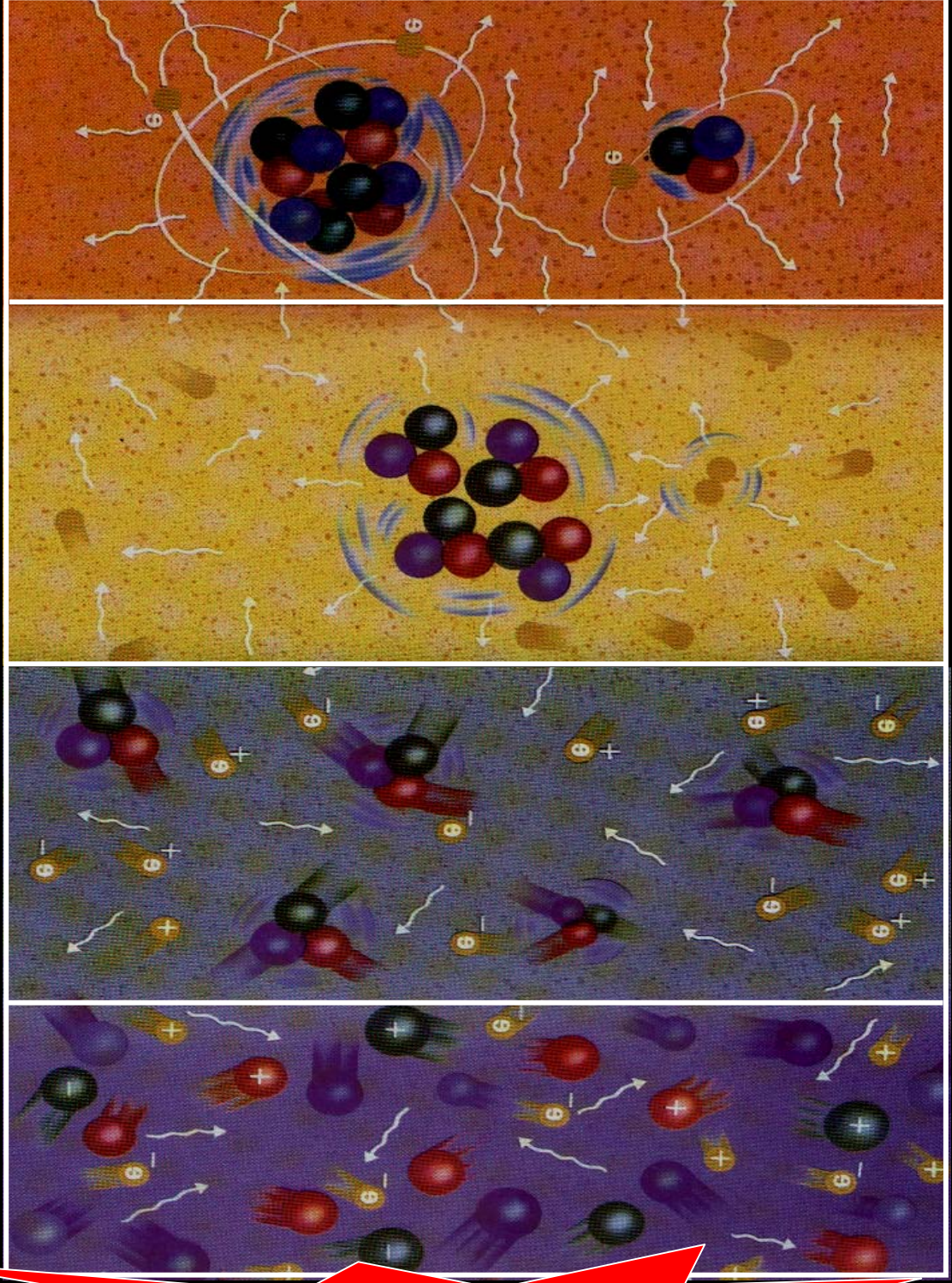
nuclei form

1-micro second

neutrons protons form

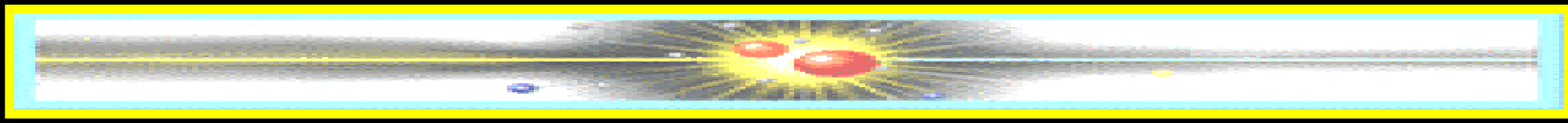
4-pico seconds

primordial soup



BANG!

EVERYTHING IN THE UNIVERSE



MICROWAVE RADIATION
SUPERCLUSTERS OF GALAXIES
CLUSTERS OF GALAXIES
STARS
PLANETS
PEOPLE
POODLES
PIGEONS
PETUNIAS
POND SCUM
PAT BUCHANAN

FROM THE PRIMORDIAL SOUP!

HORS D'OEUVRES
BEFORE SOUP ?

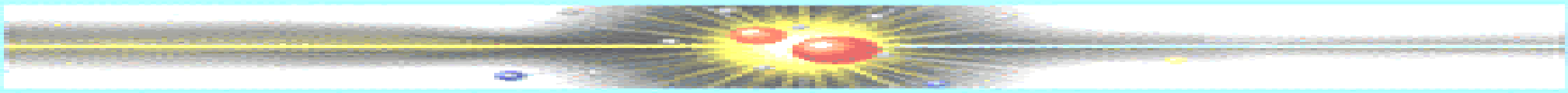
At time zero:

- infinite temperature
- infinite pressure
- infinite density
- infinite curvature

At time zero:

- spacetime singularity
- physical law breaks down
- no predictions possible
- *here be dragons!*

BEFORE PRIMORDIAL SOUP ?



NOTHING!!! (vacuum)

MUCH ADO ABOUT NOTHING:

NOTHING is something

NOTHING has energy

NOTHING can change

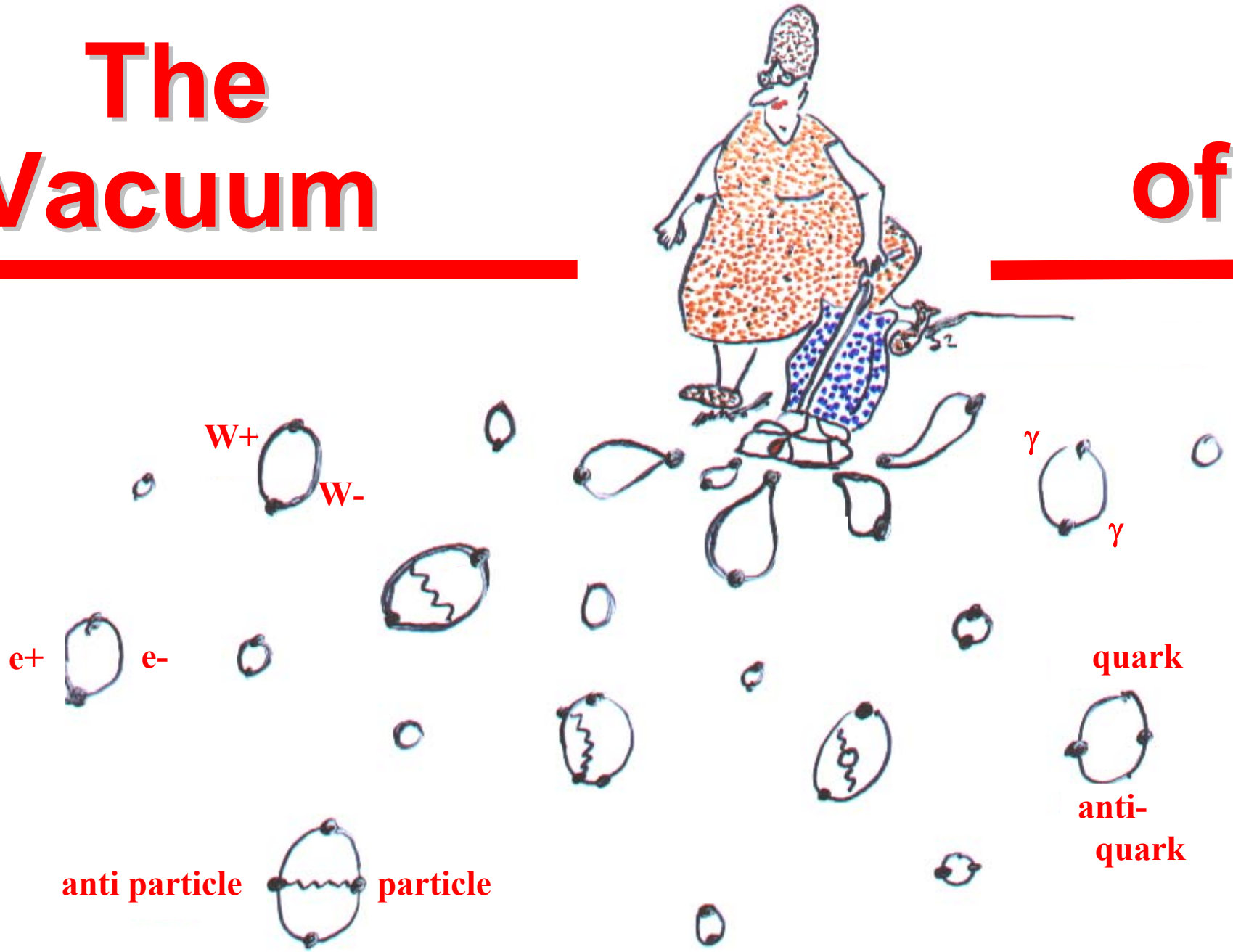
Nothing is something

This remark may be

POLITICALLY INCORRECT!!

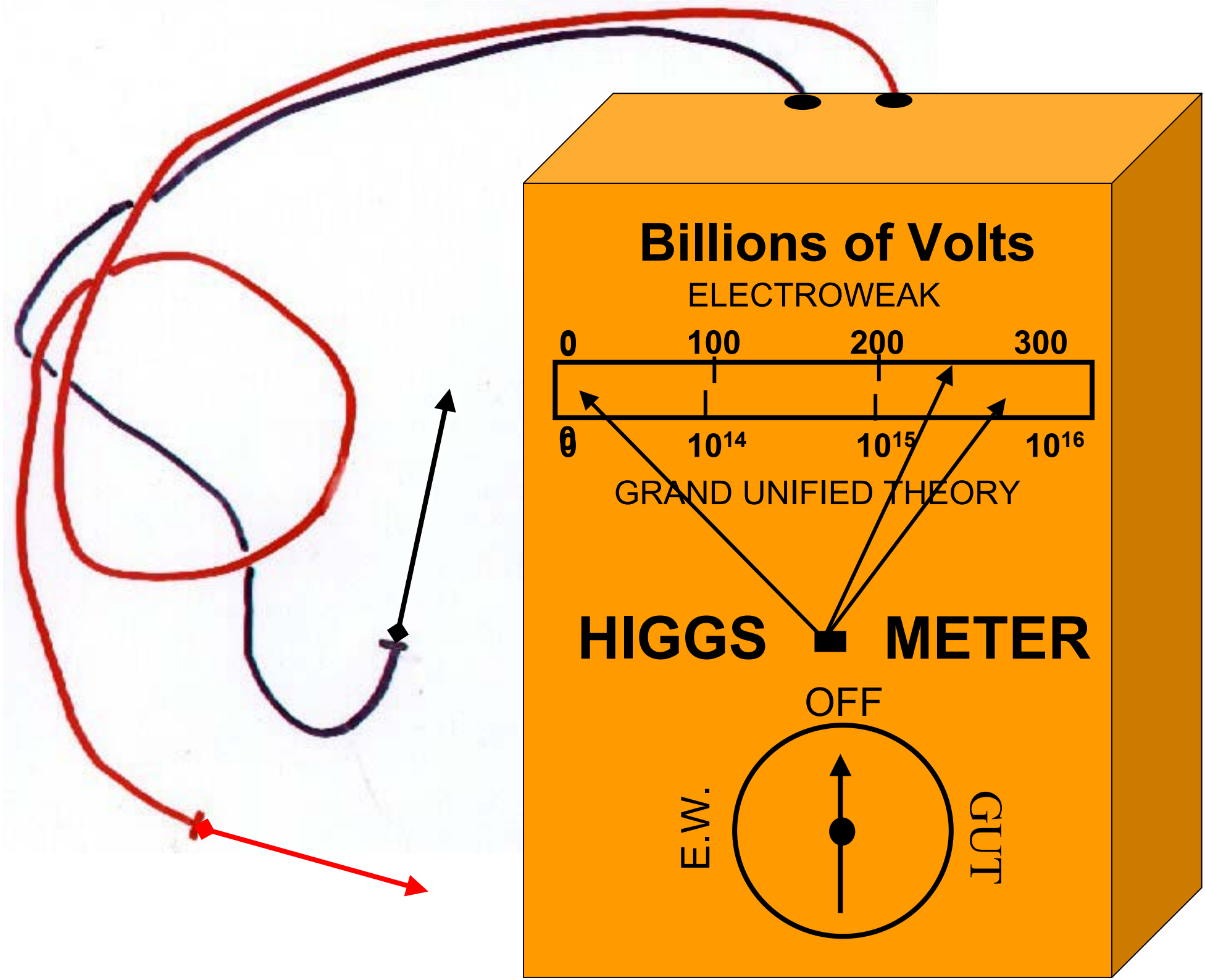
And possibly offensive to a minority of slightly more than 50% of the population

The Vacuum of Quantum Uncertainty



Nothing has energy: The Higgs potential

- The vacuum has a “Higgs potential”
- Interaction with the Higgs potential gives mass to particles


Billions of Volts
ELECTROWEAK
0
100
200
300
0
10^{14}
10^{15}
10^{16}
GRAND UNIFIED THEORY
HIGGS METER
OFF
E.W.
GUT

Every cubic inch of space is a

MIRACLE !

- Walt Whitman

- background radiation
- virtual particles
- Higgs potential

Nothing can change

- Today the density of nothingness is less than 10^{-30} grams per cc
- Before primordial soup the density of nothingness may have been larger than 10^{+30} grams per cc
- The primordial soup came from vacuum discharge (inflation)

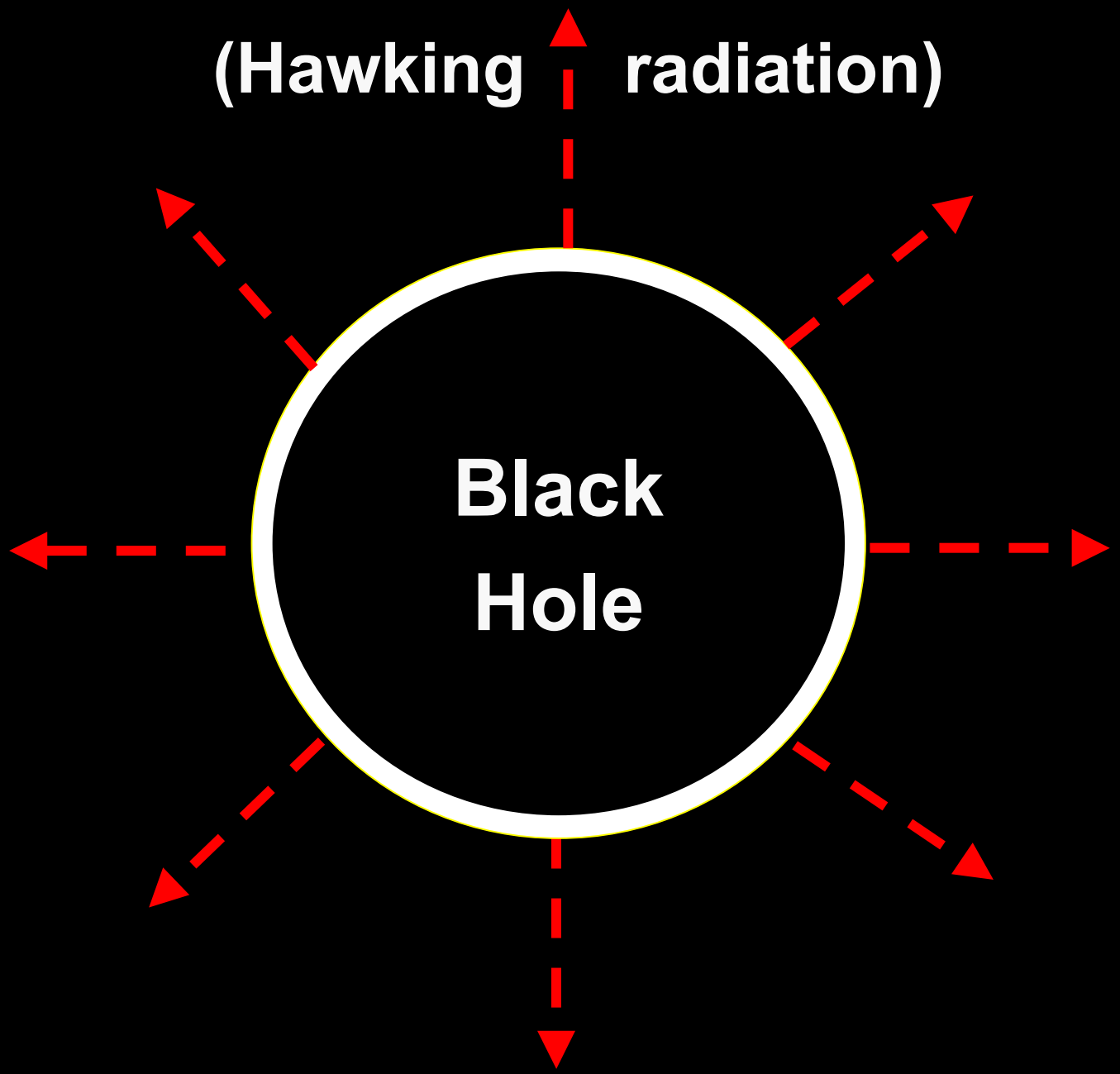
“For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation.”

- Tommy Gold

DISTURBING THE VACUUM

Strong gravitational field → particle production

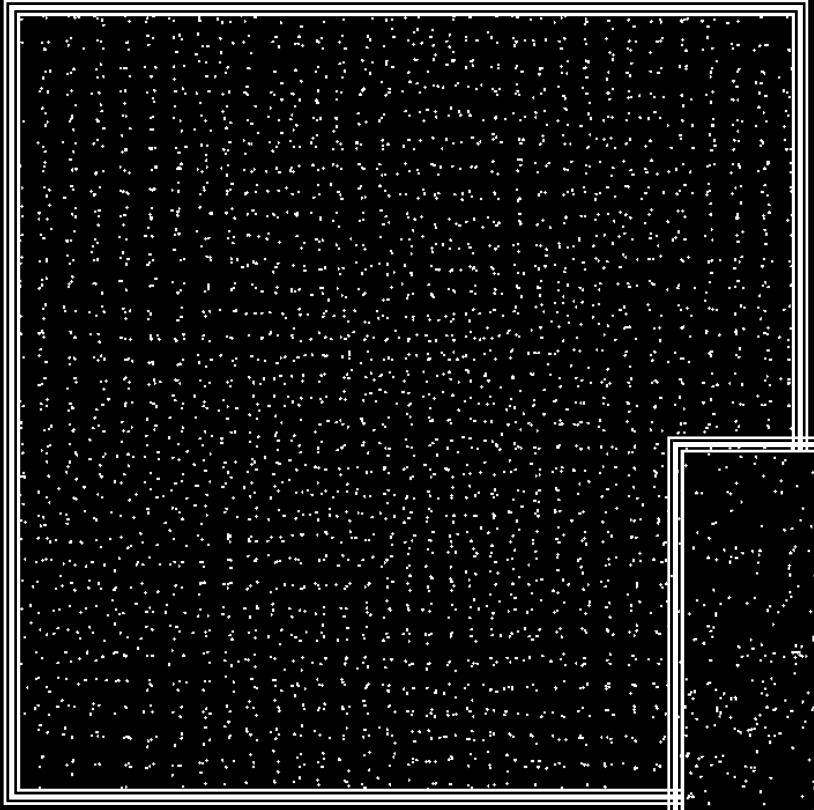
(Hawking radiation)

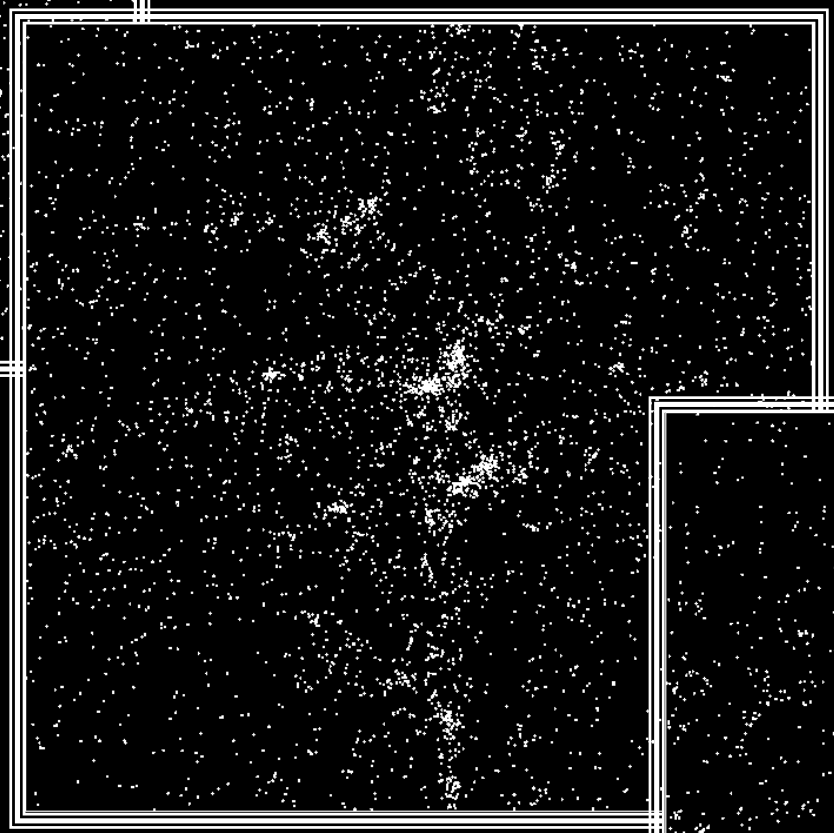


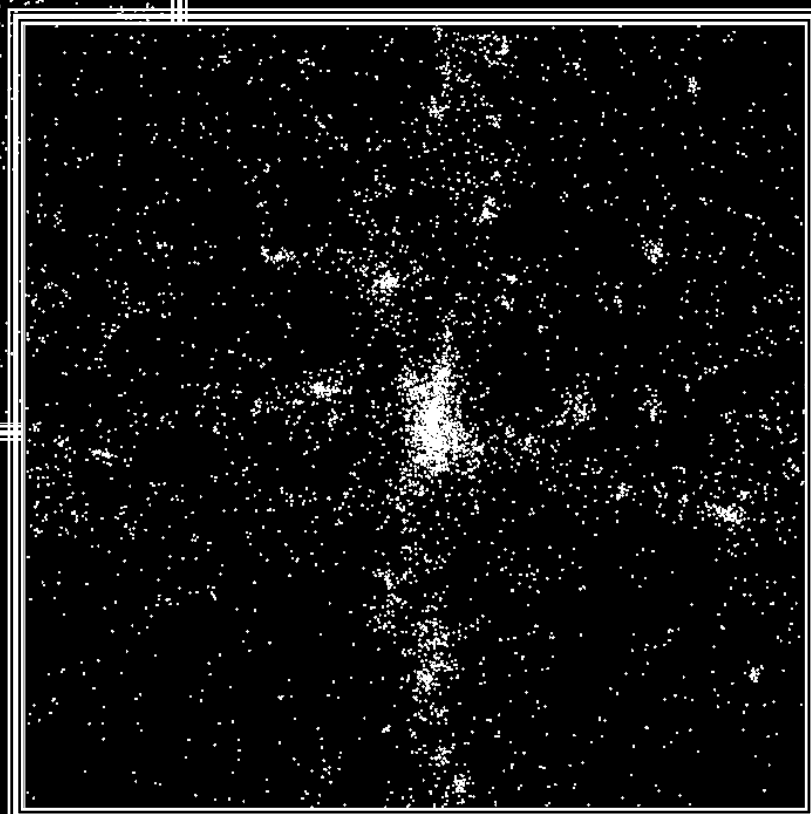
IMPERFECTIONS ARE BEAUTIFUL

Background radiation
Imperfections Observed
at the South Pole -- 2000

Seeds of structure







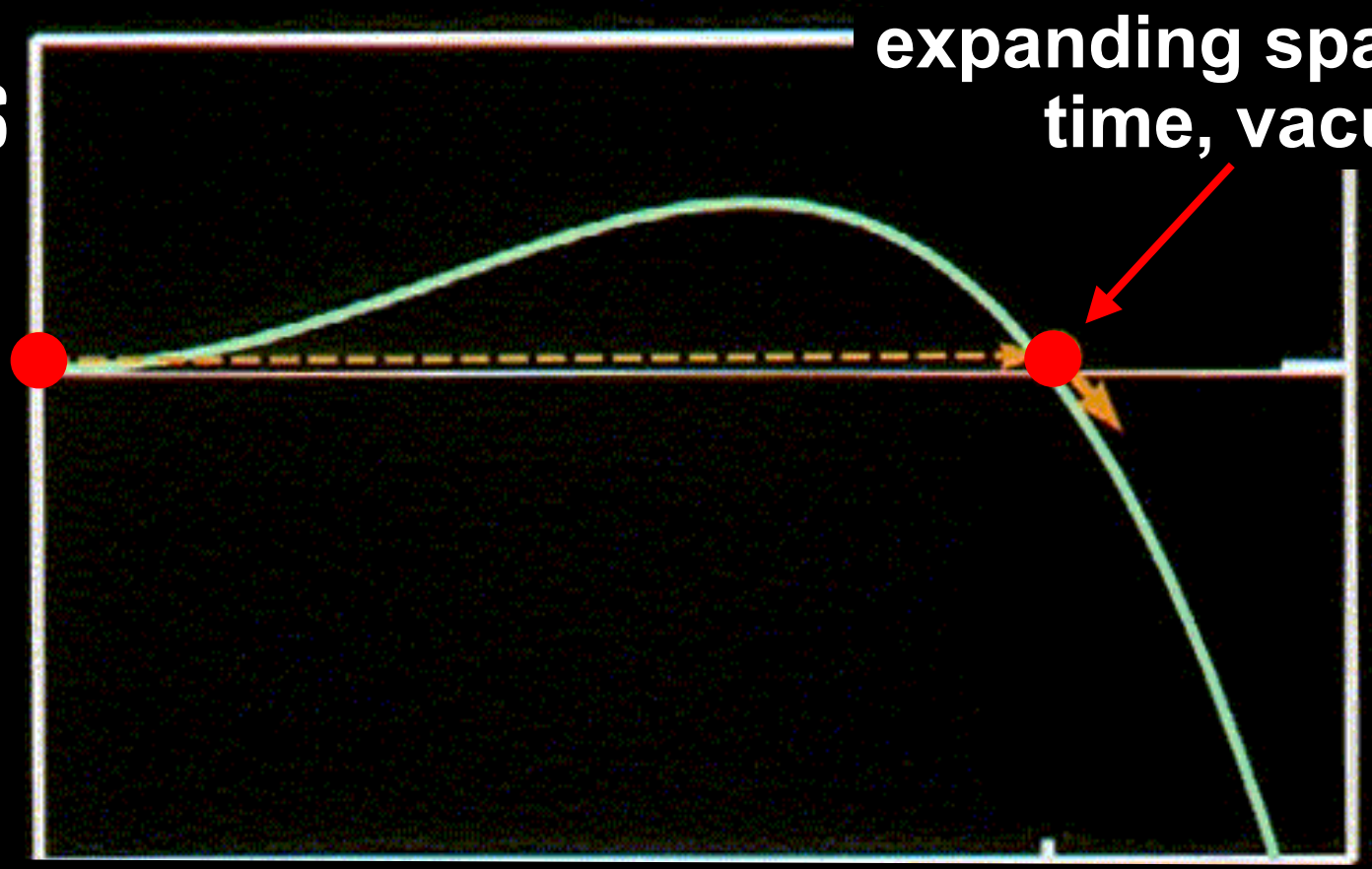
time

BEFORE NOTHING ?

NOTHING HAD A BEGINNING:

- **quantum creation of space, time, vacuum *from less than nothing.***
- **nothing is unstable -- emergence of the universe is *inevitable.***

QUANTUM TUNNELING

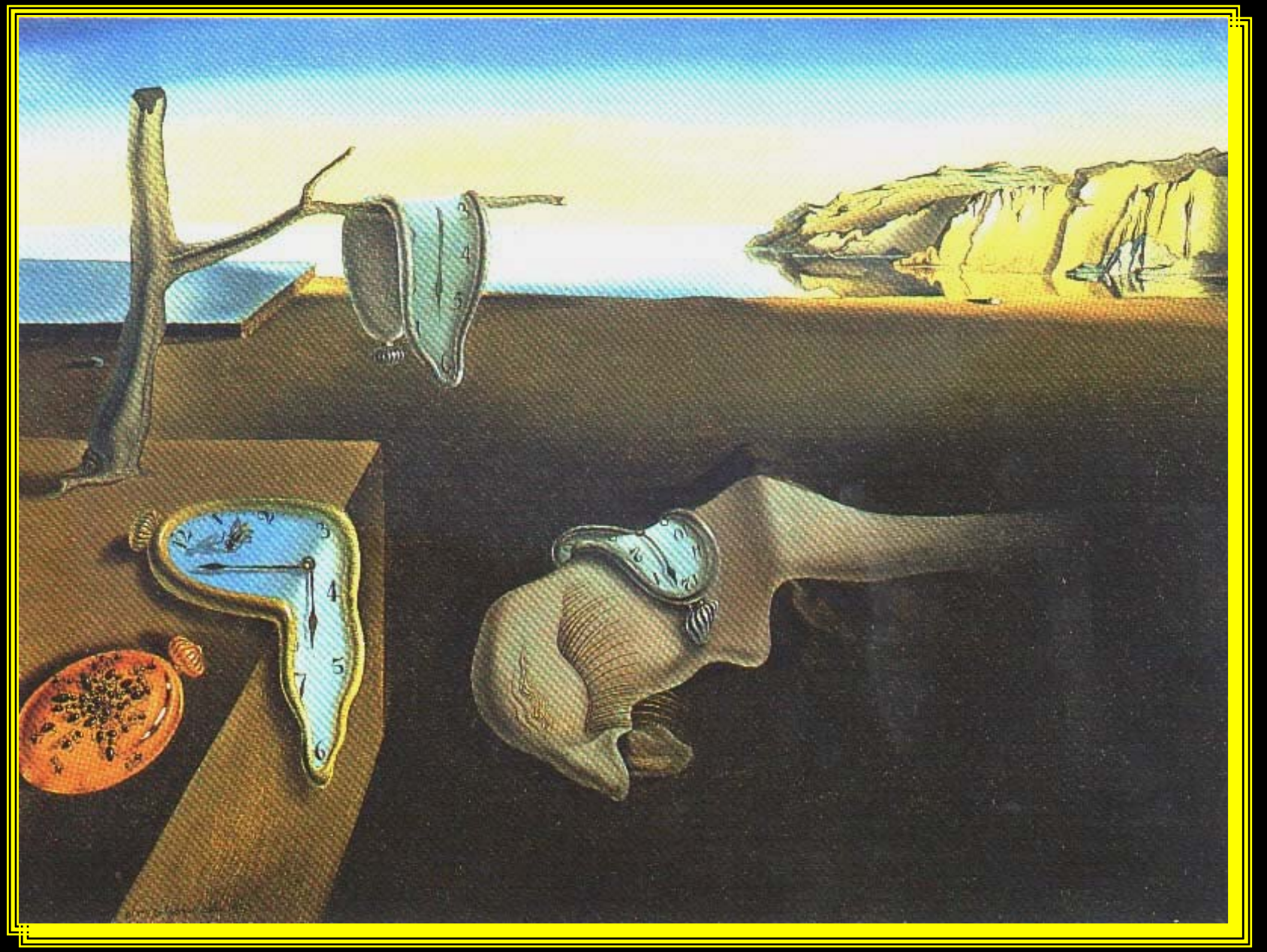


NO

...space
...time
...vacuum
...soup

Motion in "IMAGINARY TIME"

IMAGINARY TIME



BEFORE NOTHING ?

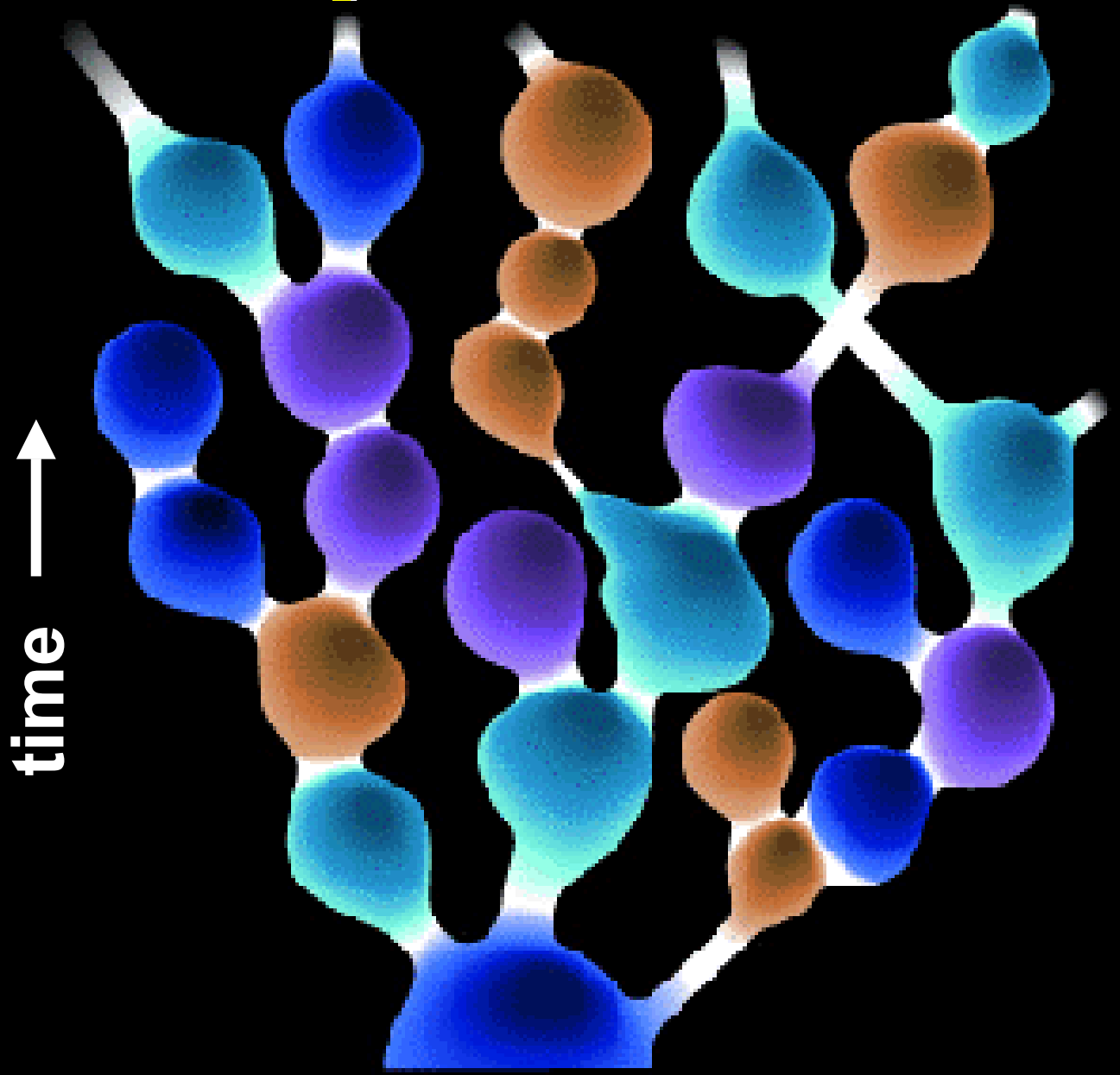
NOTHING HAD A BEGINNING:

- quantum creation of space, time, vacuum *from less than nothing.*
- nothing is unstable -- emergence of the universe is *inevitable.*

NOTHING IS ETERNAL:

- universe is *still inflating.*
- on largest scales, universe is unchanging -- *no beginning and no end.*

Quantum fluctuations lead to many different bubbles

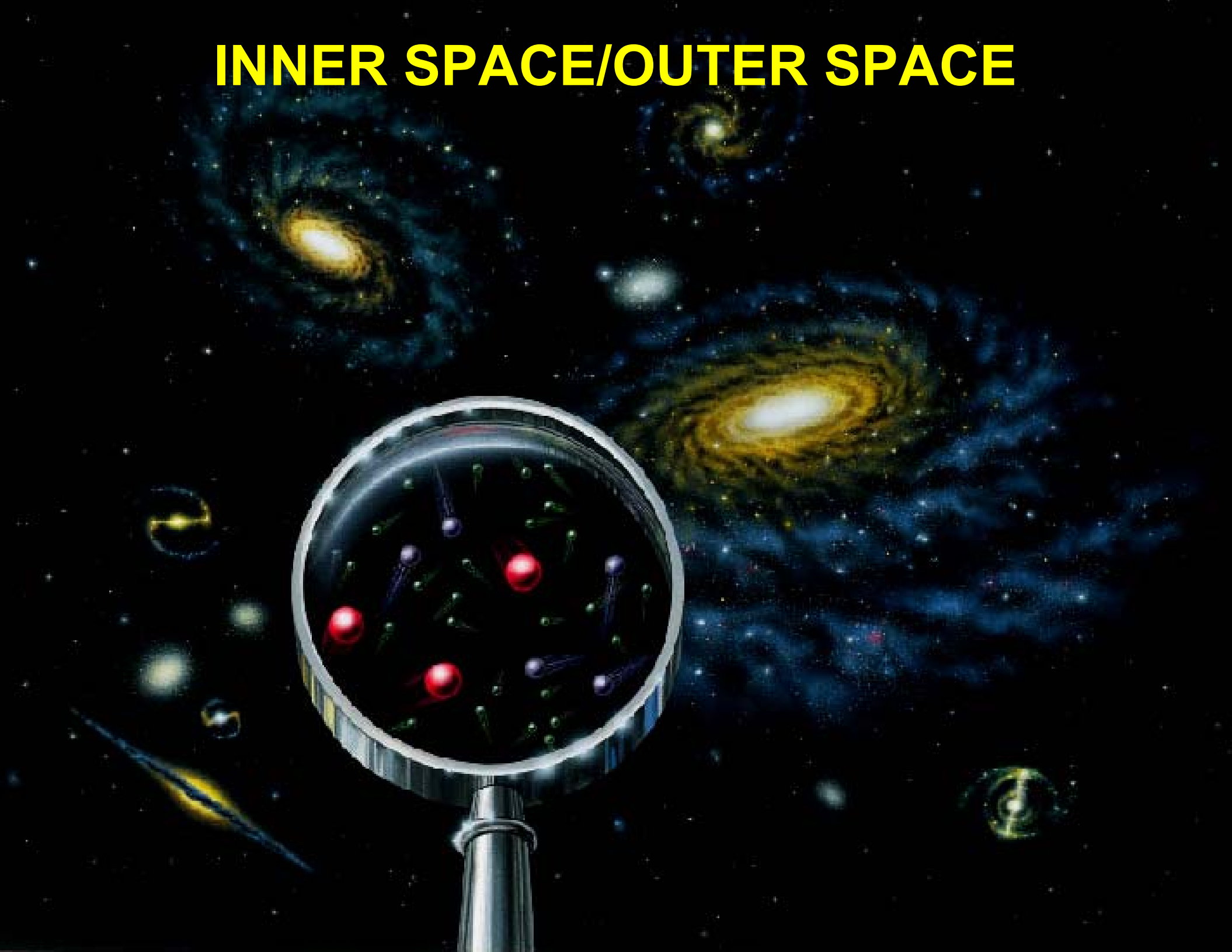


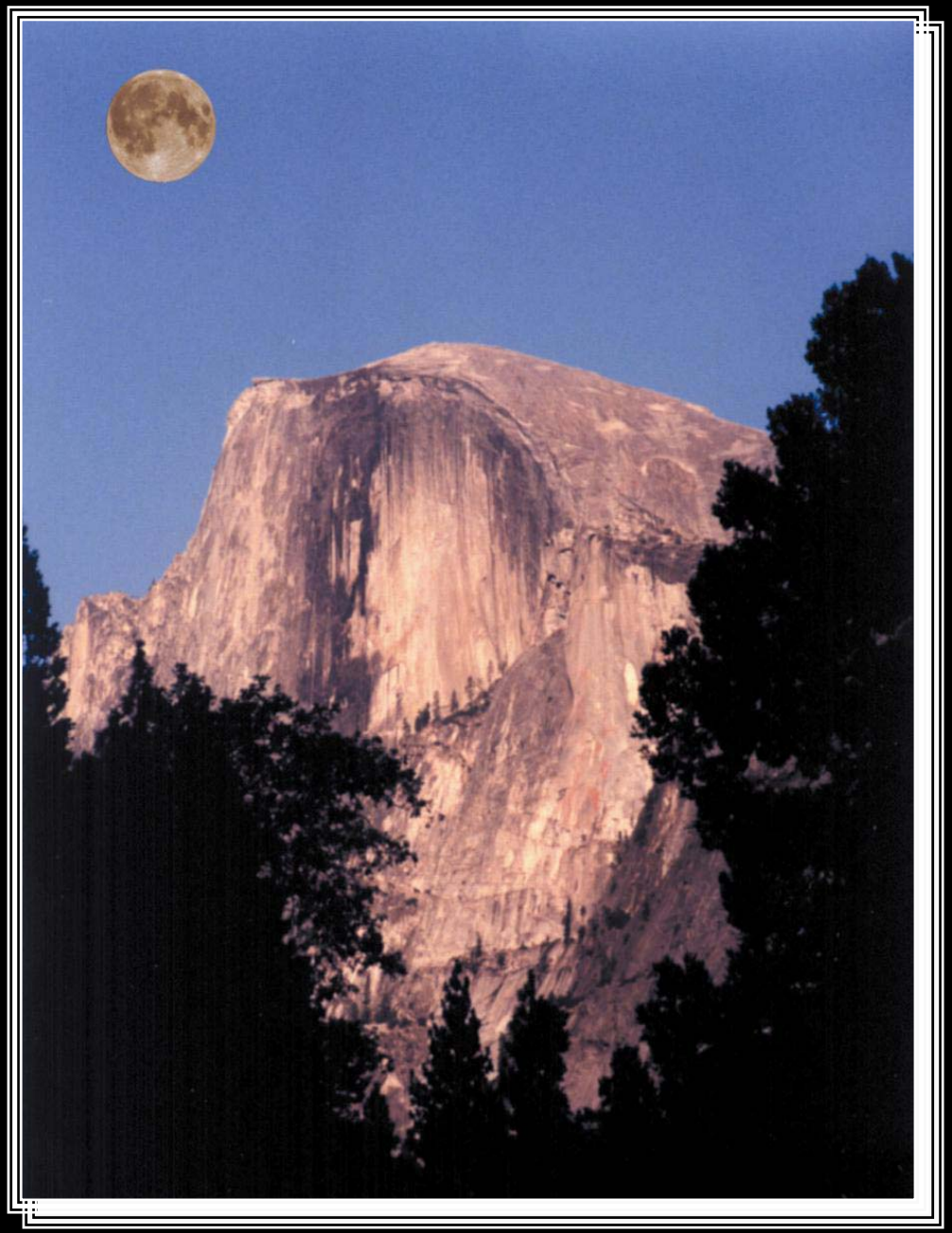
Eternally self-reproducing universe

Universe has no beginning…no end

Each bubble grows to cosmological size

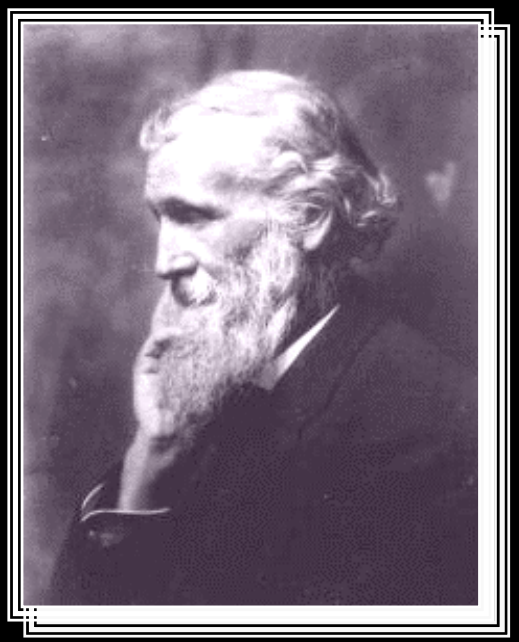
INNER SPACE/OUTER SPACE





When one tugs at a single thing in nature, he finds it hitched to the rest of the universe.

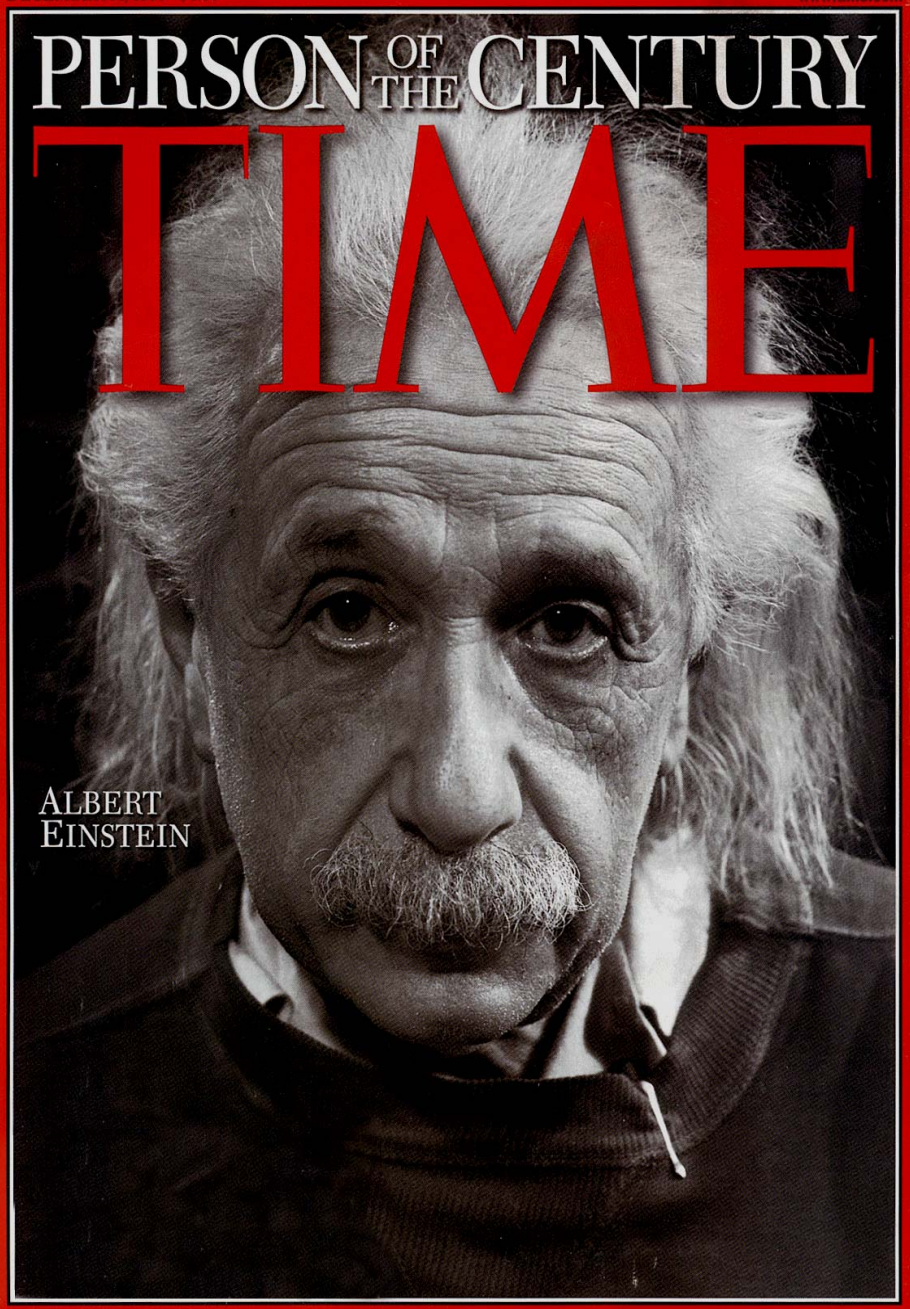
– John Muir



DECEMBER 31, 1999 $4.95 www.time.com

PERSON OF THE CENTURY

TIME



ALBERT EINSTEIN

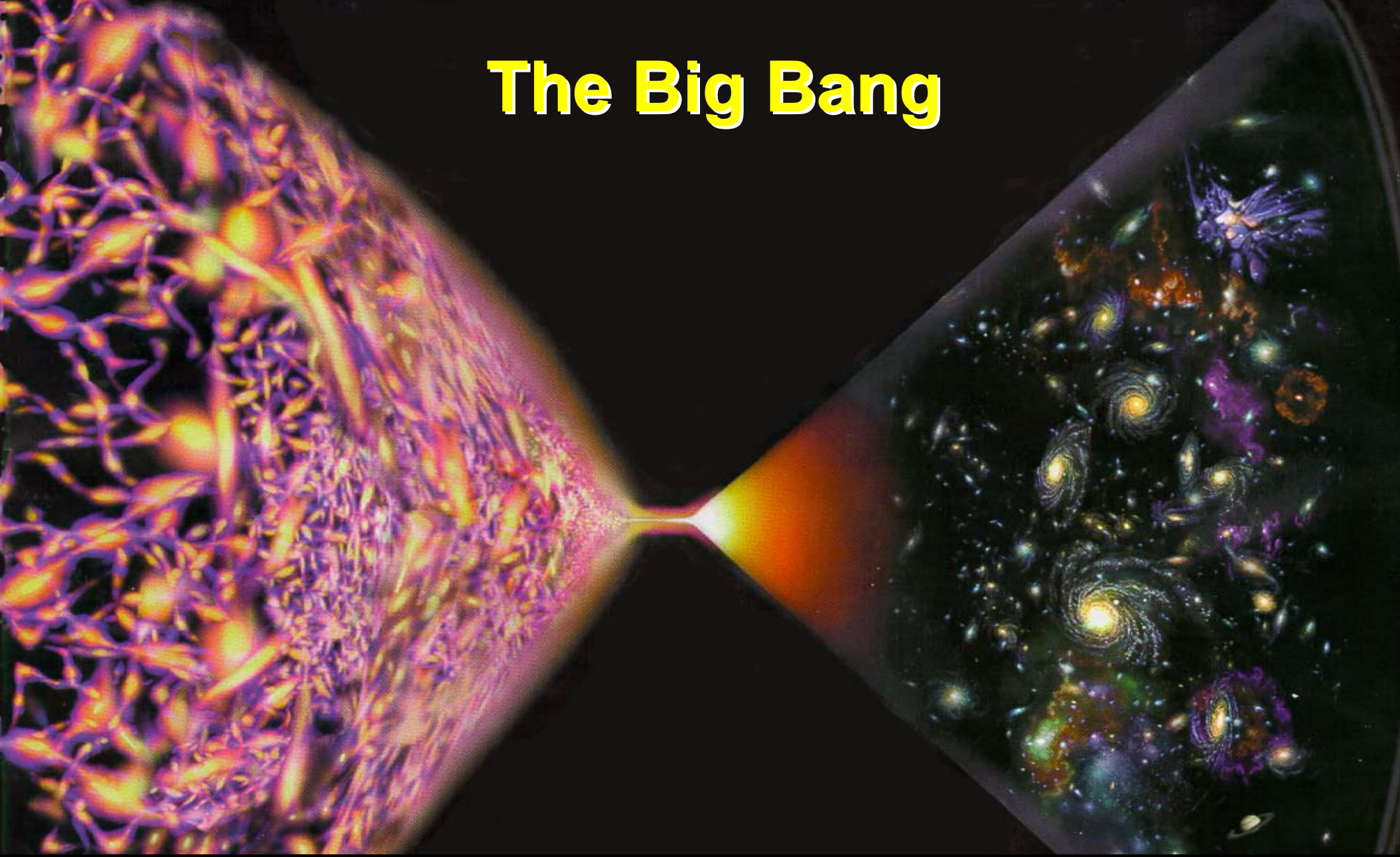
DECEMBER 31, 2099 $24.95 www.time.com

PERSON OF THE NEXT CENTURY

TIME

?

The Big Bang

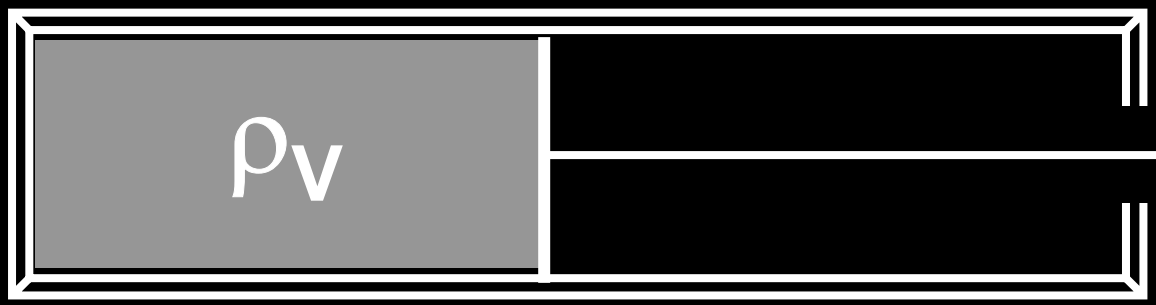


www-astro-theory.fnal.gov/Personal/rocky/

www-astro-theory.fnal.gov/Personal/rocky/saturday.ppt

Vacuum pressure

$E_1 = \rho_V V_1$



$E_2 = \rho_V V_2$

$E_2 > E_1$

had to pull piston

"negative pressure"

VACUUM ENERGY
(the weight of space)

Recent observation: 10^{-30} g cm^{-3}

Most probable answer: 0 g cm^{-3} ??

Theoretical predictions:

- **quantum field theory:** infinity!!!
- **quantum gravity:** 10^{90} g cm^{-3}
- **supersymmetry:** 10^{30} g cm^{-3}

UNIFICATION OF FORCES

- GRAVITATIONAL FORCE
- STRONG NUCLEAR FORCE
- ELECTROMAGNETIC FORCE
- WEAK NUCLEAR FORCE

Cosmic Symphony *(Harmonice Mundi)*

tempo	movement	epoch	relic
pizzicato	string dominated	10^{-43} sec.	???
prestissimo	vacuum dominated (inflation)	10^{-35} sec.	CBR fluctuations, Gravitational waves, large-scale structure
presto	radiation dominated	earlier than 10,000 yrs.	primordial nucleosynthesis
andante	matter dominated	later than 10,000 yrs.	quasars, galaxies, evolution of LSS
largo	vacuum dominated (inflation)	yesterday	acceleration of the universe